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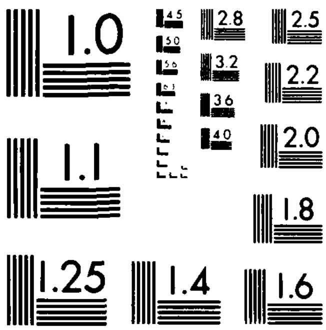

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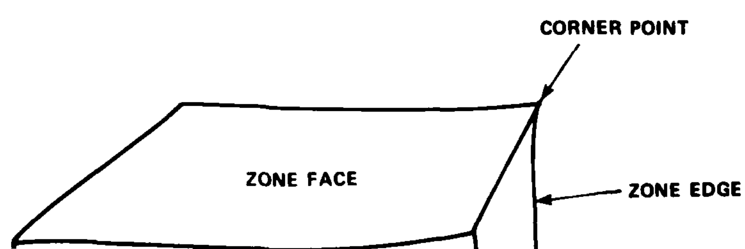

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SOLIDGEN is a computer program for generating finite element models of three-dimensional solid objects from descriptions of their external surfaces. SOLIDGEN's ease of use, power, and generality stem from the use of GPRIME surfaces to describe the surfaces of the object being modeled. Developed at the David W. Taylor Naval Ship Research and

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Development Center, GPRIME is an interactive software package which has facilities for defining a wide variety of curves and surfaces through its own geometric language. The GPRIME surface descriptions are stored in a data base which is accessible to SOLIDGEN. SOLIDGEN uses those GPRIME surfaces by simply referring to their symbolic names.

The most important step in modeling a solid object is to visualize the subdivision of the object into volumes called "zones." The subdivision of each zone into finite elements is controlled by specifying sets of reference surfaces. Isoparametric shape functions are used to obtain the coordinates of the generated grid points. The elements generated are always brick elements. Several element formats are available, including a "general connection element." Users can easily create brick elements with formats suited to their own needs from the information provided in the general connection element.

SOLIDGEN is currently operational on Control Data Corporation 6000 Series computers.

This document describes the capabilities of SOLIDGEN, tells how to use the program, and describes work in progress. Five appendices include two sample problems, instructions for expanding certain arrays for large problems, a description of the conditions needed for proper model definition, and a description of the method used to subdivide each zone into finite elements.

ACKNOWLEDGMENTS

TO THE MEMORY OF
JAMES M. McKEE

1942-1983

The Center lost a close friend with the passing of Jim McKee (coauthor of this report) on February 5, 1983. Although he was a very talented computer scientist and mathematician, and an excellent manager, he had a down-to-earth approach to all he encountered. He endeared himself among his fellow employees with his helpfulness, giving his time freely, explaining concepts, and using his technical know-how to assist in debugging computer programs no matter how busy he was, and always with the unassuming modesty of a friend helping a friend. Jim's warmth and encouragement will be remembered for a long time. He will be sorely missed.

The authors appreciate the contributions of Suzanne Wybraniec as program librarian for the GPRIME project; Dolores Wallace and Myles Hurwitz in editorial help and suggestions; Michael Golden in programming assistance, especially with software bugs; and Karen Dyson in entering this report in a computer file. Special recognition is due to the users of SOLIDGEN, especially Melvyn Marcus, who struggled with early versions of the program and made many helpful suggestions.

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ABSTRACT

SOLIDGEN is a computer program for generating finite element models of three-dimensional solid objects from descriptions of their external surfaces. SOLIDGEN's ease of use, power, and generality stem from the use of GPRIME surfaces to describe the surfaces of the object being modeled. Developed at the David W. Taylor Naval Ship Research and Development Center, GPRIME is an interactive software package which has facilities for defining a wide variety of curves and surfaces through its own geometric language. The GPRIME surface descriptions are stored in a data base which is accessible to SOLIDGEN. SOLIDGEN uses those GPRIME surfaces by simply referring to their symbolic names.

The most important step in modeling a solid object is to visualize the subdivision of the object into volumes called "zones." The subdivision of each zone into finite elements is controlled by specifying sets of reference surfaces. Isoparametric shape functions are used to obtain the coordinates of the generated grid points. The elements generated are always brick elements. Several element formats are available, including a "general connection element." Users can easily create brick elements with formats suited to their own needs from the information provided in the general connection element.

SOLIDGEN is currently operational on Control Data Corporation 6000 Series computers.

This document describes the capabilities of SOLIDGEN, tells how to use the program, and describes work in progress. Five appendices include two sample problems, instructions for expanding certain arrays for large problems, a description of the conditions needed for proper model definition, and a description of the method used to subdivide each zone into finite elements.

ADMINISTRATIVE INFORMATION

The work reported herein was performed as part of Program Element 62543N, Task 1535, Task Area SF-43-411-391 under Work Unit 1808-009 at the David W. Taylor Naval Ship Research and Development Center.

INTRODUCTION

SOLIDGEN is a computer program for generating finite element models of three-dimensional solid objects from descriptions of their external surfaces. Such objects typically are those that can be manufactured by processes such as casting,

forging, and turning. An example of a finite element model generated by SOLIDGEN is shown in Figure 1. SOLIDGEN has been developed according to specifications contained in an earlier report.[1]*

The user of SOLIDGEN must first visualize the object to be modeled as a three-dimensional array of cells known as "zones." SOLIDGEN can then be used to subdivide each zone into brick-shaped finite elements and thus to generate the desired model.

To describe the faces of the zones, SOLIDGEN uses surfaces defined by GPRIME,[2,3,4] a software package which has facilities for defining a wide variety of surfaces through its own geometric language. The surfaces so defined are identified by symbolic names. SOLIDGEN assumes that those surfaces reside in a GPRIME data base and can be retrieved from the data base by referencing the symbolic names.

The most important step in obtaining a finite element model from SOLIDGEN involves visualizing the way in which the object to be modeled can be subdivided into zones. A crucial part of that visualization is the formulation of a network of "key reference surfaces" from which the zones are formed. The object is then described to SOLIDGEN by specifying:

* The number of key reference surfaces in each of three key reference surface "families"

* Those zones formed by the network of key reference surfaces which are to be used for the model

* The names of the GPRIME surfaces which are to be associated with the faces of the zones.

Certain parameters which control the way in which SOLIDGEN subdivides the zones into finite elements must also be specified.

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*A complete listing of references is given on page 93.

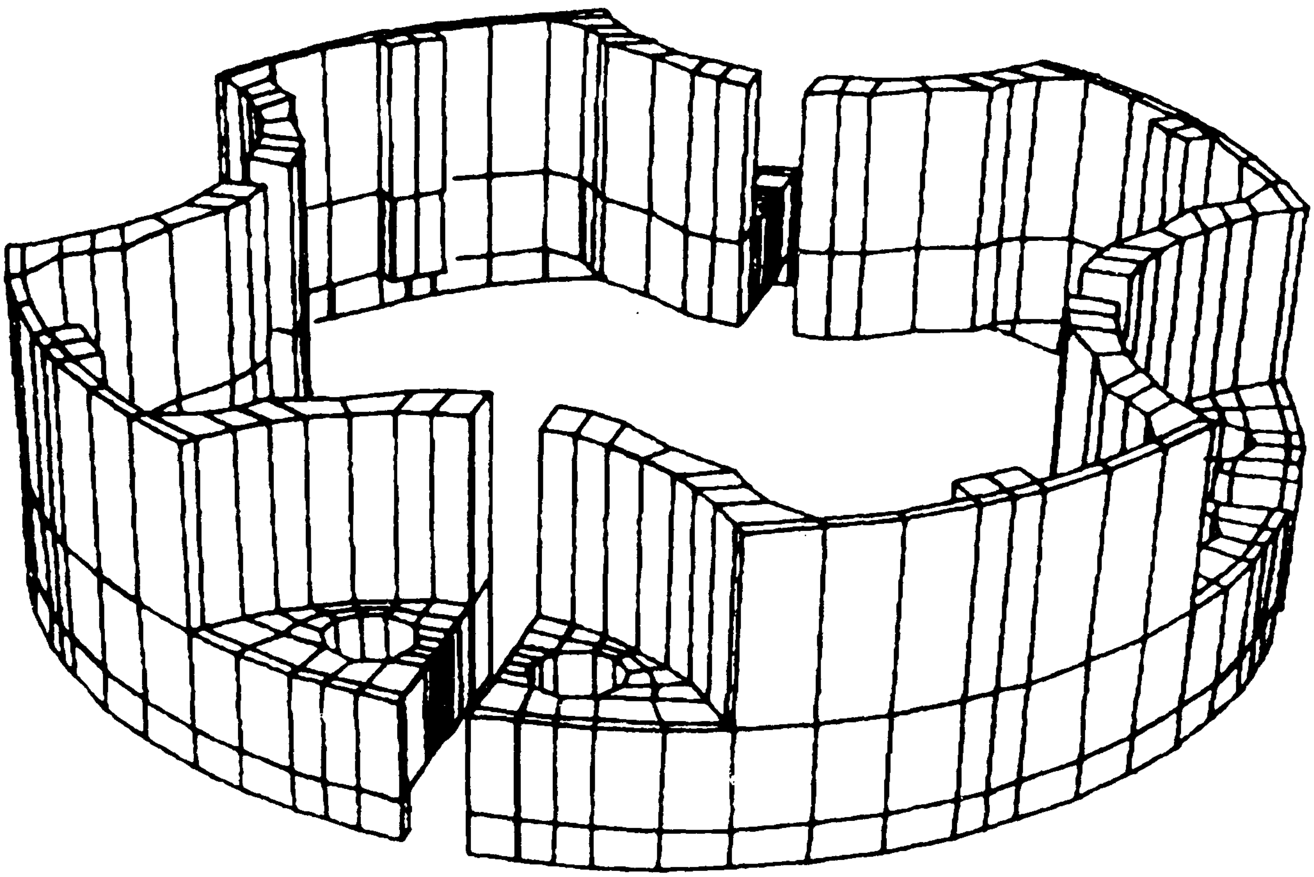


Figure 1 - Coarse Finite Element Model of a Machine Part Generated by SOLIDGEN

Once the user has created a file of GPRIME surfaces and described the object to SOLIDGEN, SOLIDGEN can generate a finite element model which includes all the element and grid point definitions necessary for finite element analysis.

SOLIDGEN can, with imagination on the part of the user, handle a wide variety of solid structural shapes. Simple shapes usually suggest one rather obvious modeling, but more complex shapes are usually amenable to a number of different modelings. In general, the advantages of automatic generation over manual generation increase with the complexity of the structural shape. In some cases, automatic generation coupled with a small amount of manual generation will greatly simplify the modeling of a complex object.

The concepts needed before SOLIDGEN can be used are explained in "SOLIDGEN CAPABILITIES." The section entitled "AN EXAMPLE" gives the new or potential user a feeling for the capabilities of SOLIDGEN without the more complex and subtle details. "USING THE PROGRAM" explains how to use SOLIDGEN. "WORK IN PROGRESS" tells about current work and future plans. The appendices provide examples and further details. Appendix A shows the application of SOLIDGEN to two sample problems. Appendix B describes how the storage capacity of certain arrays used in the SOLIDGEN code can be temporarily expanded to accommodate large problems. Appendix C contains additional details about defining the model and attempts to more fully characterize the proper definition of a model. Appendix D describes the method used for generating the model. Appendix E contains expanded versions of definitions and requirements.

SOLIDGEN can be used successfully without reading this entire report. Parts of the report are intended to help the user with some special concern, e.g., generating elements in a format not included in SOLIDGEN's repertoire of specifically formatted generated elements. Other parts are intended for the user who wishes to know about some aspect of SOLIDGEN in more depth, e.g., how the coordinates of the generated grid points are computed. Sections not required by all SOLIDGEN users are indicated throughout the report.

Although many capabilities are still to be added to SOLIDGEN, users have expressed the need for an instruction manual which applies to the currently available version of the program. This report is intended to fill that need. As new features are implemented and improved versions of SOLIDGEN become available, updated versions will be published.

SOLIDGEN CAPABILITIES

The capabilities of the SOLIDGEN program and the concepts on which it is based are described in this section, which covers the following topics:

* How the model is defined for SOLIDGEN
* How SOLIDGEN generates the model
* The finite element model

DEFINING THE MODEL

The basic building block for the model is the "zone," a volume bounded by six faces. To create a model the user visualizes a subdivision of the object into zones in a manner similar to that used to manually create a finite element model. Since GPRIME surfaces are used to describe the zone faces, the shape of each zone can be very general. The zones are related to one another by the network of key reference surfaces, which are formed from the zone faces. When the user has obtained a satisfactory subdivision of the object into zones, the key reference surfaces can be easily described.

The user's description of the object should not present unresolvable ambiguities to SOLIDGEN. This general advice is embodied in a number of requirements explicitly described in Appendix C. These requirements are part of an attempt to more fully characterize the proper description of an object.

Key Reference Surfaces and Zones

Consider a network of intersecting surfaces which form cells, each of which is bounded by six surface patches. We call the surfaces "key reference surfaces," the cells "zones," and the surface patches "zone faces." The key reference surfaces are grouped into three families: key α-reference surfaces, key β-reference surfaces, and key γ-reference surfaces. Figure 2 shows a typical zone and illustrates the terms "zone face," "zone edge," and "corner point."

Two key reference surfaces in the same family are said to be "adjacent" if, within the bounds of the structural model being defined, no key reference surfaces from the same family intervene (i.e., a path exists from any point on one of the surfaces to any point on the other surface without crossing a third key reference

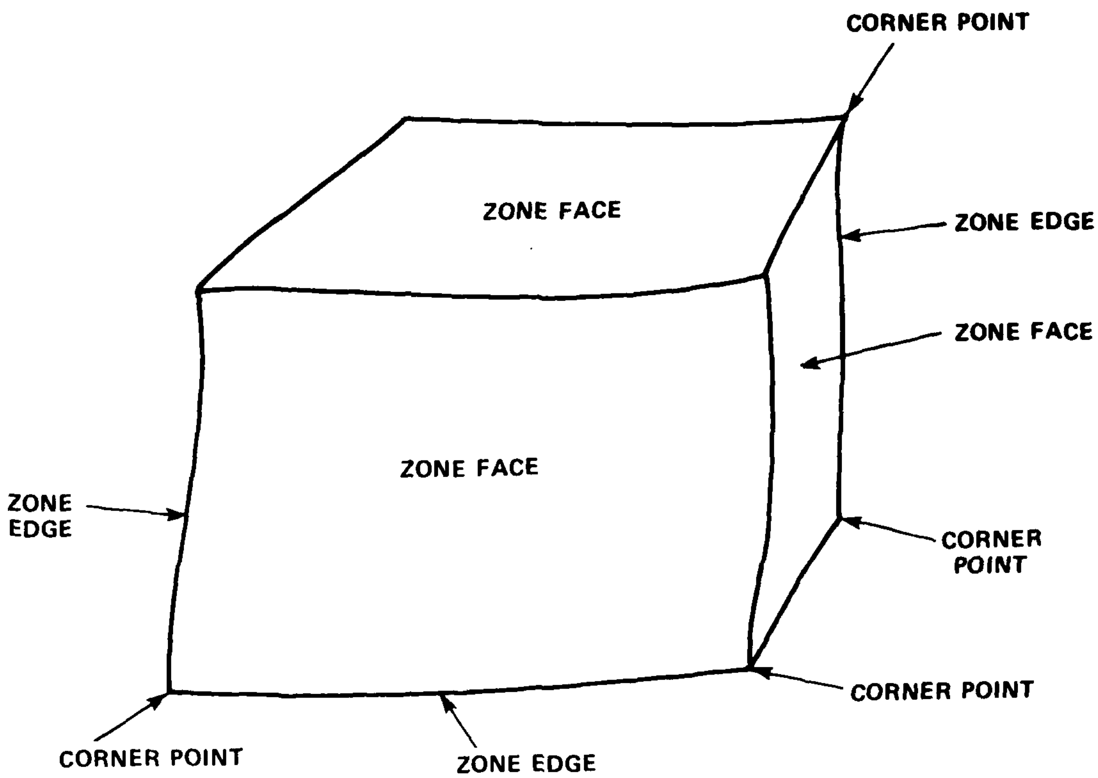


Figure 2 - Typical Zone, Showing Various Parts

surface in the same family). In each zone, two opposing zone faces belong to adjacent key α-reference surfaces, two more to adjacent key β-reference surfaces, and the remaining two to adjacent key γ-reference surfaces.

In each family, the key reference surfaces are numbered with consecutive integers, starting with 1; adjacent key reference surfaces are labeled consecutively. For example, if the key α-reference surface family were composed of three key reference surfaces, those key reference surfaces would be referred to as "Key α-Reference Surface 1," "Key α-Reference Surface 2," and "Key α-Reference Surface 3."

The zones (considered collectively) form the structural model and, when subdivided by the data generator into finite elements, yield the desired modeling. An example of an object subdivided by key reference surfaces into zones is shown in Figure 3.

There are three types of zone edges. A "Type 1" zone edge joins two zone faces which belong to the same zone and lie in adjacent key α-reference surfaces; a "Type 2" zone edge joins two zone faces which belong to the same zone and lie in adjacent key β-reference surfaces; and a "Type 3" zone edge joins two zone faces which belong to the same zone and lie in adjacent key γ-reference surfaces.

The following notation is used for compactness and readability:

$$K(1,i) \equiv \text{Key } \alpha\text{-Reference Surface } i$$

$$K(2,i) \equiv \text{Key } \beta\text{-Reference Surface } i$$

$$K(3,i) \equiv \text{Key } \gamma\text{-Reference Surface } i$$

Since the zones are an integral part of the network of key reference surfaces, certain parts of a given zone can belong to more than one zone. That is:

* A corner point can belong to as many as eight zones.
* A zone edge can belong to as many as four zones.
* A zone face can belong to one or two zones.

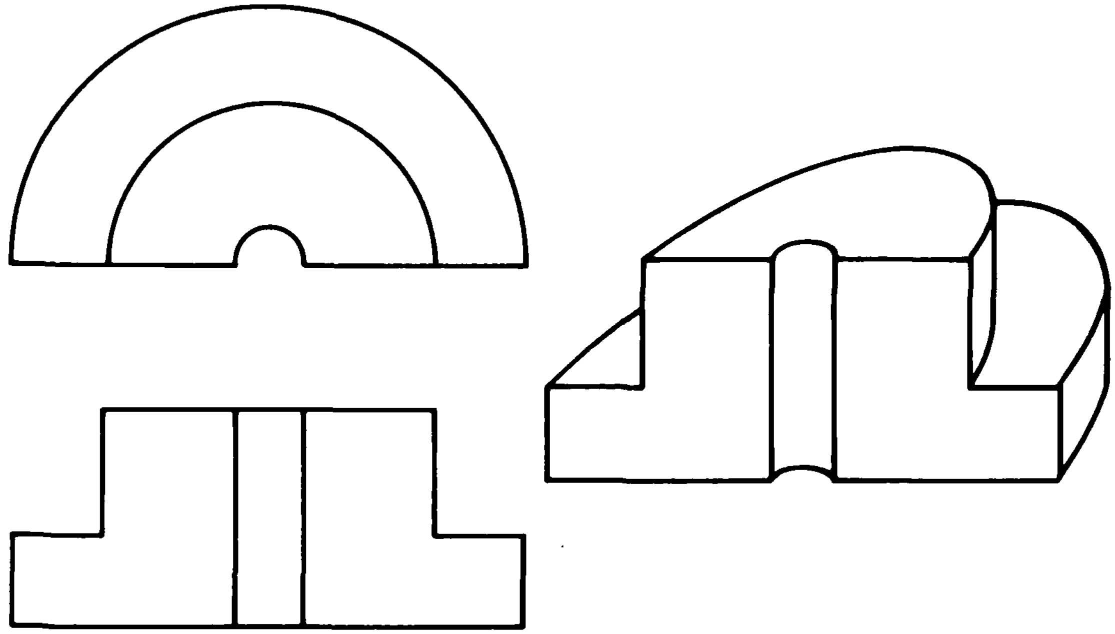


Figure 3a - Object to be Modeled

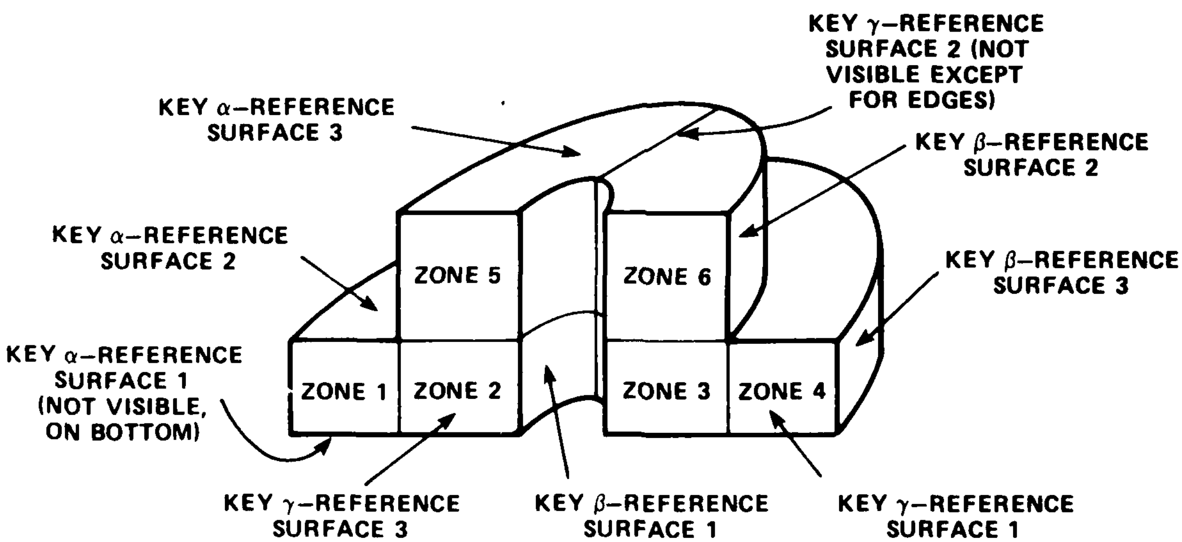


Figure 3b - Object Subdivided into Zones, with Key Reference Surfaces Shown

Figure 3 - Example of Zones and Key Reference Surfaces

The Topological Model

If each zone in the model is topologically deformed into a cube and all the relationships among the zones are preserved, we obtain a "topological model." The topological model shows how the zones are related to the key reference surfaces; at the same time it avoids the complexity which results from showing the actual shape of each zone.

In the topological model an "α-axis," a "β-axis," and a "γ-axis" can be defined as follows:

* The α-axis is perpendicular to the key α-reference surfaces and is directed from the lowest- to the highest-numbered key α-reference surface.

* The β-axis and γ-axis are defined in a similar manner.

A topological model of the object shown in Figure 3 is shown in Figure 4.

Specifying Zones

Some of the zones formed by the key reference surfaces may not be needed for the model. Such zones are left "vacant" (unused). The user specifies the "occupied" zones (zones used for the model) by labeling each such zone with a positive integer and giving the identifying numbers of certain key reference surfaces which bound the zone, i.e., i, j, and k, where K(1,i), K(1,i+1), K(2,j), K(2,j+1), K(3,k), and K(3,k+1) are the key reference surfaces which bound the zone.

Building Key Reference Surfaces

Each zone face needed by the model must be associated with exactly one GPRIME surface. This is the basic concept for building key reference surfaces.

Sometimes a key reference surface may be described simply by associating it with one GPRIME surface. When this is not possible, the key reference surface must be described by associating its zone faces with various GPRIME surfaces. The basic method for doing this is to associate a group of zone faces with one GPRIME surface. The complement of a group of zone faces, i.e., those zone faces in the key reference surface which do not belong to the group, may also be

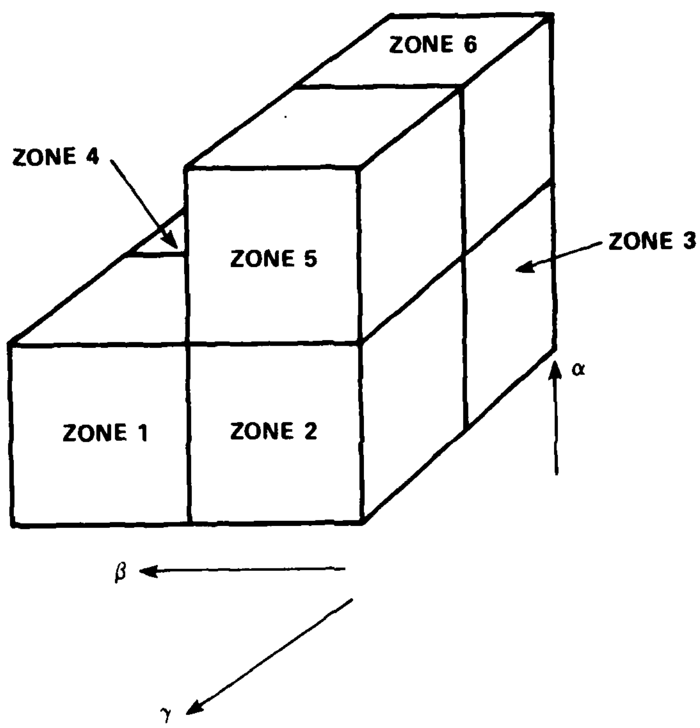


Figure 4 - Topological Model of Object Shown in Figure 3

associated with a GPRIME surface. Each zone face is specified by identifying the zone to which it belongs. A zone so named must have one zone face which belongs to the key reference surface being described. If a zone face belongs to two occupied zones, it may be specified by identifying both of those zones.

When a GPRIME surface is to be associated with one or more zone faces in a key reference surface, it must be sufficient in extent to describe the zone face or zone faces; however, it is permissible that part of it not be needed for describing any zone face. That is, a GPRIME surface does not have to coincide with the zone face or zone faces it is being used to describe. Figures 5 and 6 illustrate this concept. Figure 5 shows a typical zone with the zone faces to be described, i.e., associated with GPRIME surfaces; Figure 6 shows GPRIME surfaces that could be used to describe the zone faces. Note that, on the other hand, the need to avoid ambiguity in describing the object tends to limit the extent of GPRIME surfaces used for describing zone faces.

Guidelines For Choosing Key Reference Surfaces

The first step the user must take in modeling a structure is to visualize and define three families of key reference surfaces which subdivide the model into zones. Although there is no well-defined procedure for doing this, the user should try to visualize how the structure could be subdivided into volumes (zones), each of which is bounded by six surfaces (zone faces).

Once the model has been subdivided into zones, the user may arbitrarily choose the way in which the surfaces bounding the zones are to constitute the three families of key reference surfaces. For example, the user may look at one zone and designate pairs of opposing faces as members of the three respective families of key reference surfaces. The pattern established for that zone holds for adjacent zones and, hence, for the entire model.

There is one convention that must be followed during the process of designating the key reference surface families in relation to the surfaces bounding the zones: The α, β, and γ axes must form a right-handed system. This convention must be followed to ensure proper orientation among the grid points for each of the generated elements.

Some GPRIME surfaces will occur "naturally," i.e., in connection with the object's external surfaces, but other GPRIME surfaces will have to be constructed

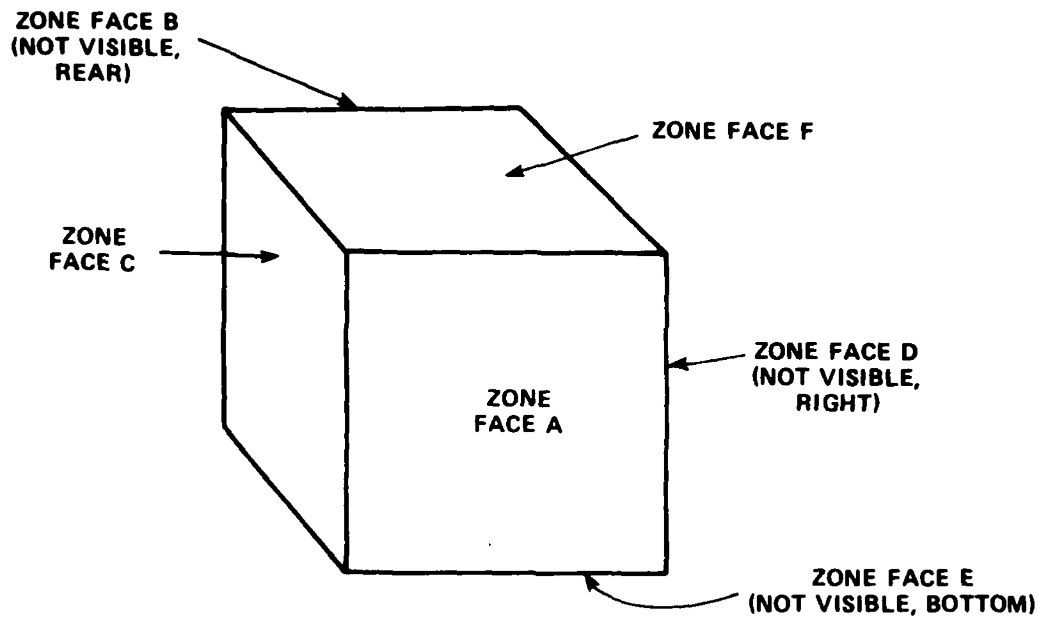


Figure 5 - Typical Zone

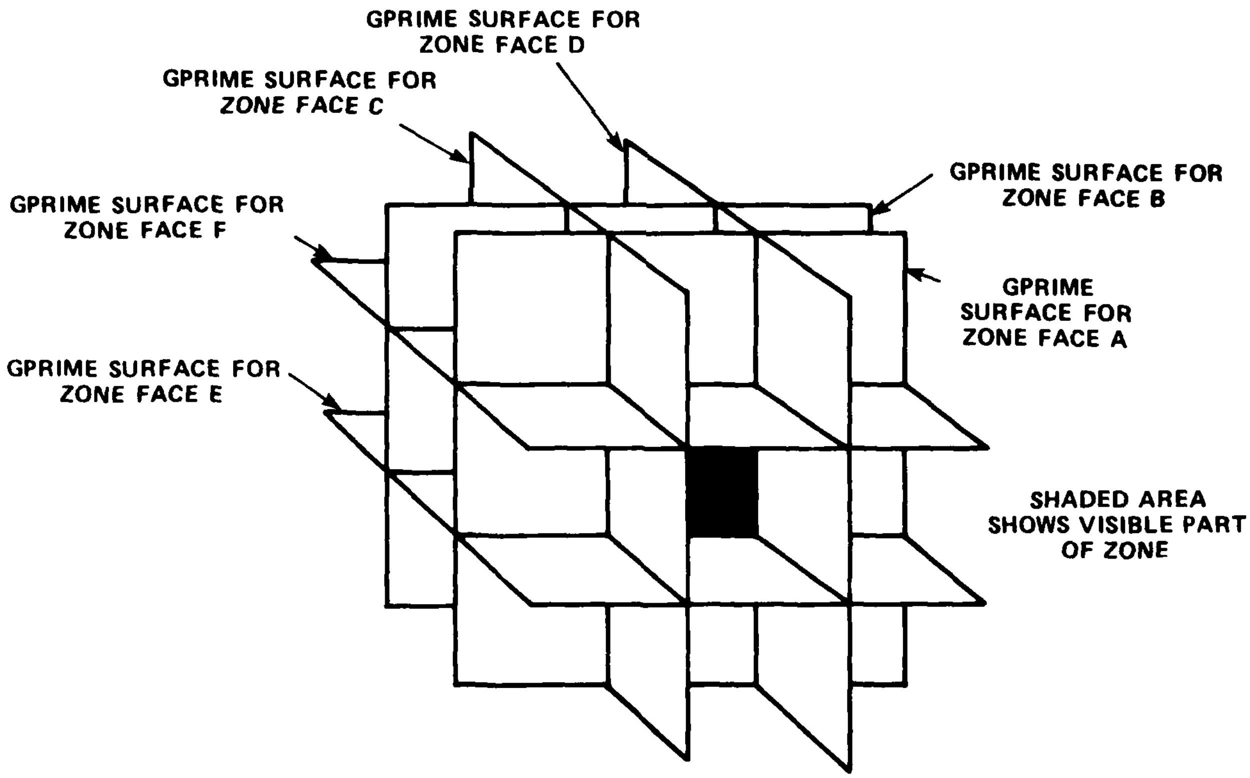


Figure 6 - Association of Zone Faces with GRPIME Surfaces for Zone Shown in Figure 5

by the user for the sole purpose of helping to subdivide the object into zones. We can refer (loosely) to the latter kind of GPRIME surfaces as "constructed GPRIME surfaces." Each zone face which lies on an external surface of the object is defined as a "natural zone face." Each zone face which lies (except possibly for its edges) entirely inside the object is defined as a "constructed zone face." Each GPRIME surface associated only with constructed zone faces is defined as a "constructed GPRIME surface," and each key reference surface formed entirely from constructed zone faces is defined as a "constructed key reference surface." Examples of most of these terms are given in each of the sample problems in Appendix A.

Interior Reference Surfaces and Generated Elements

The generated model contains two kinds of "reference surfaces": key reference surfaces and interior reference surfaces. Key reference surfaces have already been described. Interior reference surfaces subdivide the zones into the desired generated elements, which will always be brick elements. An example of a brick element is shown in Figure 7. There is a set of interior reference surfaces for each pair of adjacent key reference surfaces in a family. Both kinds of reference surfaces run through the model (i.e., they cross zone boundaries), ensuring the compatibility of the generated elements at the zone faces. The key reference surfaces must be specified by the user, but the interior reference surfaces are created by SOLIDGEN. The user is required to specify only the number of interior reference surfaces that lie between each two adjacent key reference surfaces in the same family.

Figure 8 illustrates the terms "element face" and "element edge." There are three types of element edges. A "Type 1" element edge joins two element faces, both of which belong to the same element and each of which lies in an α-reference surface. "Type 2" and "Type 3" element edges have similar definitions but refer to β- and γ-reference surfaces, respectively.

Format of Generated Elements

SOLIDGEN generates brick elements in several formats. There are two classes of generated elements:

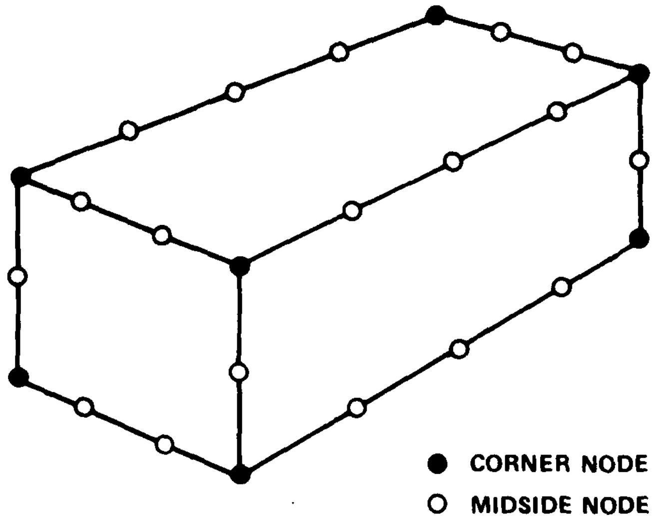


Figure 7 - Example of Brick Element

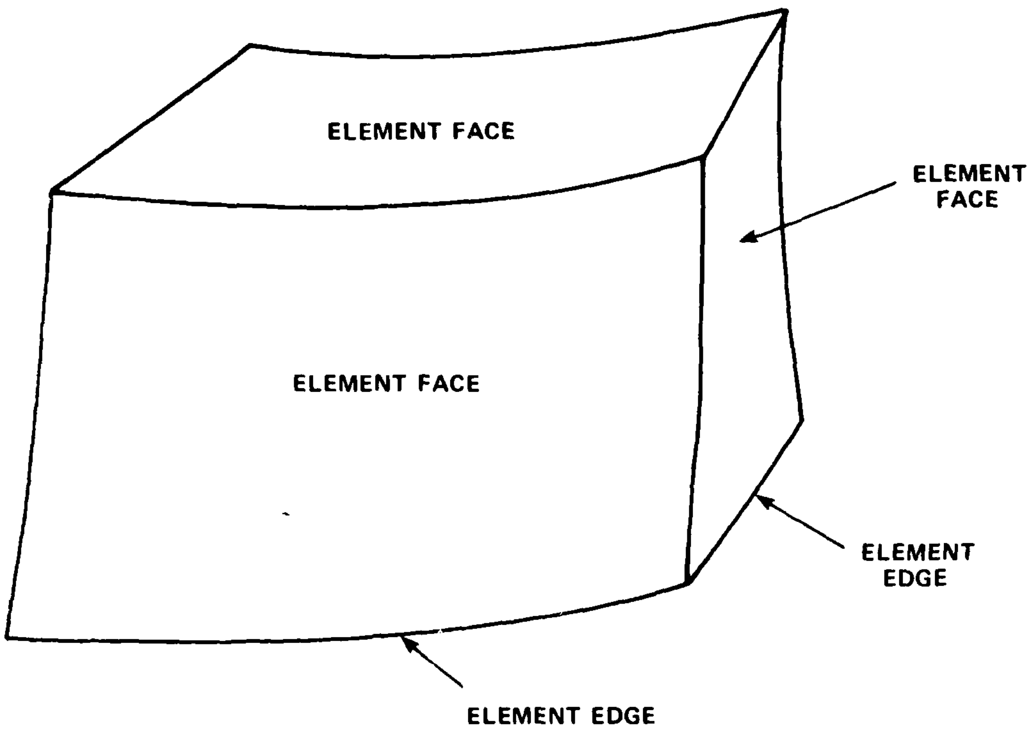


Figure 8 - Illustration of Terms Associated with Elements

1. The general (nonspecific) connection element

2. Specific connection elements (several formats)

The user may select any of these formats as needed. The general (nonspecific) connection element is intended for the user whose needs are not met by any of the specific connection element formats. Each user can easily create a brick element with a format that suits the modeling requirements from the information provided in such an element. When the general connection element is used, the number of midside nodes on each element edge type must be specified. The following specific connection elements, which are all related to NASTRAN,[5,6] are available: CIS3D8, CIS3D20, CIHEX1, CIHEX2, CIHEX3, CHEXA1, and CHEXA2.

Subdividing the Object

Sometimes an object which is too large or too complicated to be modeled in its entirety by SOLIDGEN may be modeled by subdividing it into smaller objects (components), modeling each of the components, and then forming a model of the entire object from the models of the components. Because the grid points and elements of the entire model must be uniquely identified, the user must specify the following two parameters for each model of a component:

* N_G = Integer to be added to each grid point number
* N_E = Integer to be added to each element identifier

Forming the model of the entire object also requires the merging of grid points at all locations at which two or more models of components are to be joined.

GENERATING THE MODEL

SOLIDGEN generates the model zone by zone, concentrating on one zone at a time. The finite elements for each zone are generated as follows:

* The descriptions of the key reference surfaces are used to compute the coordinates of "zone defining points." There are two kinds of zone defining points: corner points

and midside points. Midside points describe the interiors of the zone edges.

* Isoparametric shape functions are used to subdivide the zone into finite elements.

* "Surface correction" is performed on certain grid points so that they conform to the descriptions of the key reference surfaces.

Generally, this method yields good results, generating desirably shaped finite elements while providing grid points which portray the zone faces accurately.

Since the use of SOLIDGEN requires no knowledge of the method used for generating the model, the reader who wants to know the details of that method is referred to Appendix D.

THE GENERATED MODEL

The finite element model generated by SOLIDGEN includes all the element and grid point definitions necessary for finite element analysis.

Grid Points

The coordinates of the generated grid points and the numbers which identify those grid points are contained on NASTRAN[6] GRID cards.

Elements

Several definitions will be used in the descriptions of the general connection element and the various specific connection elements.

Within a given family of reference surfaces one reference surface is defined to "precede" another reference surface if the first reference surface lies on the same side of the second reference surface as the first key reference surface. The "global number" of any reference surface (which may be either a key reference surface or an interior reference surface) is defined as N+1, where N = total number of reference surfaces that precede the reference surface under consideration.

The following terms are defined for a generated element which lies within the zone bounded by K(1,i), K(1,i+1), K(2,j), K(2,j+1), K(3,k), and K(3,k+1):

* The "lower α-reference surface" is that α-reference surface which bounds the element and is closer to K(1,i).

* The "upper α-reference surface" is that α-reference surface which bounds the element and is closer to K(1,i+1).

* The "lower β-reference surface" is that β-reference surface which bounds the element and is closer to K(2,j).

* The "upper β-reference surface" is that β-reference surface which bounds the element and is closer to K(2,j+1).

* The "lower γ-reference surface" is that γ-reference surface which bounds the element and is closer to K(3,k).

* The "upper γ-reference surface" is that γ-reference surface which bounds the element and is closer to K(3,k+1).

The General Connection Element. Each user can easily create a brick element with a suitable format from the information provided in such an element. Each general connection element in the generated model will contain the following information:

1. The location of the element in the generated model

2. The grid point numbers for the generated grid points that constitute the corner nodes and midside nodes.

The reader who is not using the general connection element will not need the remainder of this subsection.

The location of the element in the generated model is given by the global numbers of the lower α-, β-, and γ-reference surfaces.

The generated grid points are ordered as follows:

1. The grid points that lie in the lower γ-reference surface (Refer to this group of grid points as Group 1)

2. The grid points that lie between the lower and upper γ-reference surfaces (Group 2)

3. The grid points that lie in the upper γ-reference surface (Group 3).

In turn, the ordering within Group 1 and Group 3 occurs as follows:

1. The grid points that lie in the lower β-reference surface

2. The grid points that lie between the lower and upper β-reference surfaces (Group 4)

3. The grid points that lie in the upper β-reference surface.

The ordering within Group 4 occurs as follows:

1. The grid points that lie in the lower α-reference surface.

2. The grid points that lie in the upper α-reference surface.

The ordering within Group 2 occurs as follows:

1. The grid points that lie in the lower β-reference surface (Group 5)

2. The grid points that lie in the upper β-reference surface (Group 6).

The ordering within Group 5 and Group 6 occurs as follows:

1. The grid points that lie in the lower α-reference surface

2. The grid points that lie in the upper α-reference surface.

To supplement and clarify the first explanation, it is necessary to introduce some additional notation. R(i,j,k) is defined as the grid point at a corner node, where i, j, and k indicate the location of the grid point as follows:

$$* \quad i = \begin{cases} 1 & \text{Lower } \alpha\text{-reference surface} \\ 2 & \text{Upper } \alpha\text{-reference surface} \end{cases}$$

$$* \quad j = \begin{cases} 1 & \text{Lower } \beta\text{-reference surface} \\ 2 & \text{Upper } \beta\text{-reference surface} \end{cases}$$

$$* \quad k = \begin{cases} 1 & \text{Lower } \gamma\text{-reference surface} \\ 2 & \text{Upper } \gamma\text{-reference surface} \end{cases}$$

$E_m(i,j,k)$ is defined as the grid points which represent the midside nodes on a Type m element edge, where i, j, and k indicate the location of the element edge as follows:

$$* \quad i = \begin{cases} 0 & \text{Not needed for this element edge} \\ 1 & \text{Lower } \alpha\text{-reference surface} \\ 2 & \text{Upper } \alpha\text{-reference surface} \end{cases}$$

$$* \quad j = \begin{cases} 0 & \text{Not needed for this element edge} \\ 1 & \text{Lower } \beta\text{-reference surface} \\ 2 & \text{Upper } \beta\text{-reference surface} \end{cases}$$

$$* \; k = \begin{cases} 0 & \text{Not needed for this element edge} \\ 1 & \text{Lower } \gamma\text{-reference surface} \\ 2 & \text{Upper } \gamma\text{-reference surface} \end{cases}$$

Note that $i = 0$ for each Type 1 element edge, $j = 0$ for each Type 2 element edge, and $k = 0$ for each Type 3 element edge.

This notation will be used to describe Group 1, Group 2, and Group 3 grid points. Group 1 and Group 3 are as follows, where $k = 1$ for Group 1 and $k = 2$ for Group 3:

$$R(1,1,k)$$

$$E_1(0,1,k)$$

$$R(2,1,k)$$

$$E_2(1,0,k)$$

$$E_2(2,0,k)$$

$$R(1,2,k)$$

$$E_1(0,2,k)$$

$$R(2,2,k)$$

Group 2 is as follows:

$$E_3(1,1,0)$$

$$E_3(2,1,0)$$

$$E_3(1,2,0)$$

$$E_3(2,2,0)$$

<u>The Specific Connection Elements</u>. All these elements will be identified in terms of their bounding reference surfaces as follows:

Element Identification Number (EID) $= 10^4 n_1 + 10^2 n_2 + n_3$, where

n_1 = global number of lower α-reference surface,

n_2 = global number of lower β-reference surface, and

n_3 = global number of lower γ-reference surface

With the Element Identification Number constructed in this manner, n_1, n_2, and n_3 should be apparent from casual inspection.

AN EXAMPLE

A simple example will introduce new or potential users of SOLIDGEN to its capabilities.

The first step in modeling an object with SOLIDGEN is to visualize a network of the key reference surfaces used to represent the external surfaces of the object and also to subdivide the interior of the object. The key reference surfaces are grouped into the key α-, β-, and γ-reference surface families. The volumes or zones thus formed, when considered together, define the entire object. Some of the zone faces will lie on the external surfaces of the object; the remaining zone faces lie in the object's interior.

The object to be modeled is shown in Figure 9. Figure 10, a topological model formed by topologically deforming each zone into a cube, shows the relationship of the key reference surfaces to the zones but avoids the complications of showing the actual shape or physical details of each zone. Thus, the topological model is a "schematic" of the object.

In Figure 10, Zone 1 is bounded by the following six key reference surfaces:

* Key α-Reference Surface 2

* Key α-Reference Surface 3

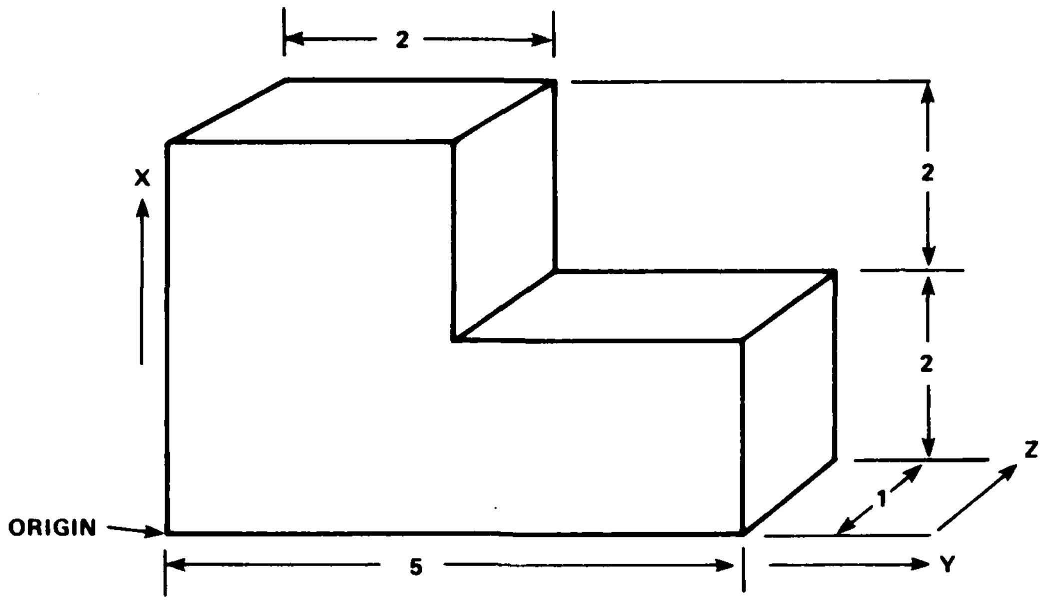


Figure 9 - Object to be Modeled

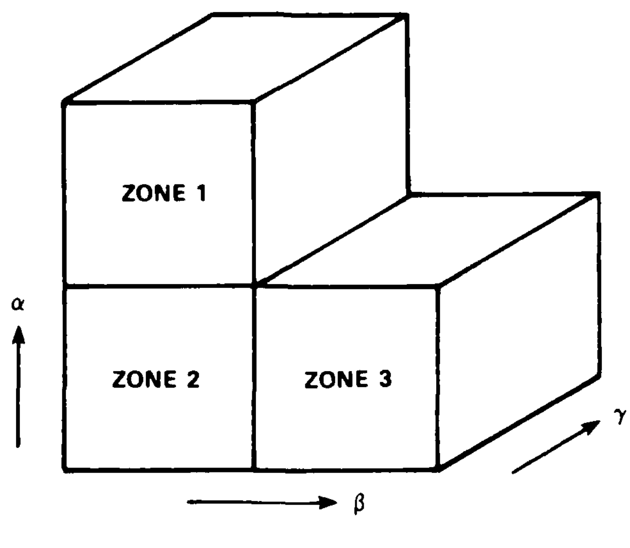


Figure 10 - Topological Model

* Key β-Reference Surface 1
* Key β-Reference Surface 2
* Key γ-Reference Surface 1
* Key γ-Reference Surface 2.

The object's actual shape is represented by using a GPRIME surface to describe each zone face. The following GPRIME input could be used to describe the GPRIME surfaces for this example:

```
COMMENT.   S1   PLANE   X = 0
S1,PLANE,0,0,5,0,1,X
COMMENT.   S2   PLANE   X = 2
S2,PLANE,2,0,5,0,1,X
COMMENT.   S3   PLANE   X = 4
S3,PLANE,4,0,5,0,1,X
COMMENT.   S4   PLANE   Y = 0
S4,PLANE,0,0,4,0,1,Y
COMMENT.   S5   PLANE   Y = 2
S5,PLANE,2,0,4,0,1,Y
COMMENT.   S6   PLANE   Y = 5
S6,PLANE,5,0,4,0,1,Y
COMMENT.   S7   PLANE   Z = 0
S7,PLANE,0,0,4,0,5,Z
COMMENT.   S8   PLANE   Z = 1
S8,PLANE,1,0,4,0,5,Z
```

The descriptions of GPRIME surfaces are included in the "geometric definition file" which, in turn, is used to produce the "geometry file" needed by SOLIDGEN.

The geometric definition file, which is created by the user, contains analytical descriptions of the GPRIME surfaces and thus is readable to the user, but the geometry file is in a format more readily processed by the computer. The geometry file is automatically created from the geometric definition file by GPRIME.

Finally, the user must put together a "SOLIDGEN Input Deck" which, except for the GPRIME surface descriptions, contains the description of the model. A SOLIDGEN Input Deck which could be used for this example is shown in Figure 11.

The cards marked "1" specify the number of key reference surfaces in each family. For example, there are three key reference surfaces in the key α-reference surface family.

The cards marked "2" tell which zones are occupied (used for the model) and label those zones. The bounds of each zone are always specified by naming the key reference surface with the lower number.

The cards marked "3", "4", and "5" describe, respectively, the key α-, β-, and γ-reference surfaces. For example, Key α-Reference Surface 3 is described by S3. (The "1" that appears just before the GPRIME surface name on each card indicates that the entire key reference surface is described by one GPRIME surface.)

The cards marked "6", "7", and "8" control the subdivision of the zones into generated elements by indicating the number of interior reference surfaces to be placed between each two adjacent key reference surfaces. These cards control, respectively, the interior α-, β-, and γ-reference surfaces. For example, three interior reference surfaces are to be placed between Key γ-Reference Surfaces 1 and 2.

The cards marked "9" specify that CIHEX2 elements are to be generated.

The SOLIDGEN Input Deck and GPRIME surfaces just described were used to generate the model shown in Figure 12.

USING THE PROGRAM

SOLIDGEN is currently operational on Control Data Corporation (CDC) 6000 Series computers.

```
                          "AN EXAMPLE"
         BEGIN BULK

                                      1        1
 (1)     KEY
                   3          3          2
 (9)     GENERATED ELEMENT FCRMAT
         CIHEX2
 (6)     INTERIOR ALPHA
             1     1
 (7)     INTERIOR BETA
             2     1
 (8)     INTERIOR GAMMA
             3
         START ZONES
 (2)               1          2          1          1
                   2          1          1          1
                   3          1          2          1

         START KEY
         START ALPHA
 (3)               1          1 S1
                   2          1 S2
                   3          1 S3

         START BETA
 (4)               1          1 S4
                   2          1 S5
                   3          1 S6

         START GAMMA
 (5)               1          1 S7
                   2          1 S8

         END INPUT
         ENDDATA
```

Figure 11 - SOLIDGEN Input Deck

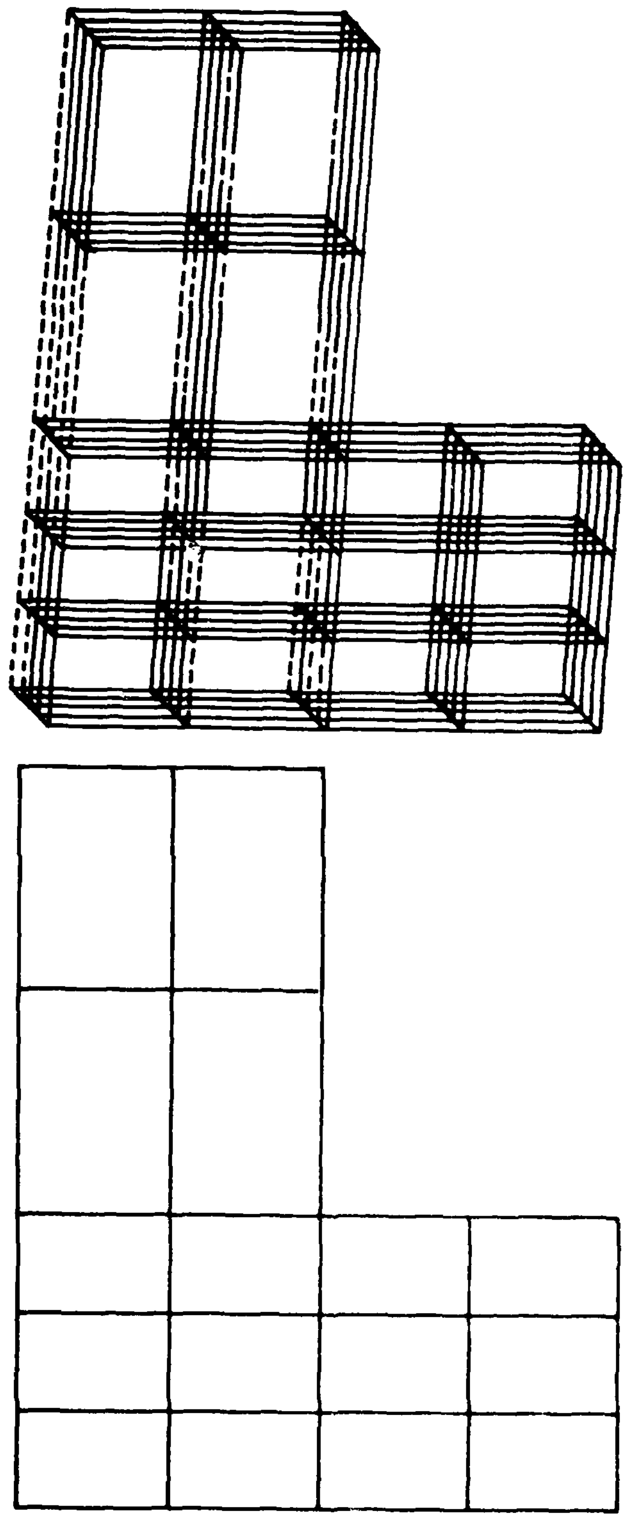


Figure 12 - Generated Model

The card deck used for running SOLIDGEN (and therefore for generating the model) consists of two components:

1. Control cards
2. The SOLIDGEN Input Deck

These two components, separated by an "End-of-Record" card (7, 8, and 9 punches in column 1), are described in this section. (Although the procedure described here assumes that a card deck is being used, SOLIDGEN can also be run from an interactive terminal).

The execution of SOLIDGEN causes the generated model to appear in two places:

1. The output listing from the line printer
2. The file whose LFN (local file name) is DATA.

The file DATA may be catalogued on a permanent file for computer processing (e.g., plotting, finite element analysis).

The PROGRAM card which resides in the main program of the SOLIDGEN code assigns its input/output files as follows:

1. INPUT - the card reader
2. OUTPUT - the line printer
3. DATA - a "local" (disk) file

A number of error messages can appear in the line printer output listing during a SOLIDGEN run. These messages are largely self-explanatory, but a brief description of the kinds of information provided in the messages is given here. Each message contains the following items:

* Location Code - an integer which serves as an identifier for the error message. Each type of problem is assigned a unique integer, which helps the experienced user to rapidly identify the type of problem.

* Message - an explanation (at length) of the exact nature of the problem that has occurred. When appropriate, parameters associated with the problem and meaningful to the user are mentioned.

* Suggested Remedy

* Subroutine Name - name of the subroutine that was being executed when the problem occurred. (Although not of interest to most users, this item is potentially useful to those who might become familiar with the code.)

THE GEOMETRY FILE

The "geometry file," which must be created before SOLIDGEN can be used to generate the model, contains descriptions of the GPRIME surfaces associated with the zone faces of the model. These descriptions are in a form which can be used by the GPRIME intersection subroutines. SOLIDGEN uses these subroutines to obtain the zone defining points and thus to create the model. SOLIDGEN references the descriptions by means of the GPRIME surface names.

Because the geometry file must be understandable to the GPRIME intersection subroutines, the user must create a "geometric definition file," a collection of analytical descriptions of the GPRIME surfaces. The geometric definition file is built (in a hierarchical manner) from analytical descriptions of the GPRIME Surfaces.[2] (The SOLIDGEN geometry file is identical to the file referred to by GPRIME[2] as the "User Master File.") The GPRIME software is then used to create (automatically and in one simple step) a geometry file from the user's geometric definition file.

The control cards for making the computer run which creates the geometry file from the geometric definition file are shown in Figure 13. (Except for an "End-of-File" card (6, 7, 8, and 9 punches in column 1) at the end, no other

```
              C          JOB CARD
              C             CHARGE CARD
A ────────► ATTACH,GEOMDEF,     GEOMETRIC DEFINITION FILE    .
              MSACCES,XXXX.     XXXX IS MASS STORE ACCESS PASSWORD
              ATTACH,GPRIME,ID=GPRM.
B ────────► GPRIME,      GEOMETRY FILE     ,NEW,INFILE=GEOMDEF.
```

Figure 13 - Control Cards for Creating Geometry File
from Geometric Definition File

cards are needed in the deck. Although the procedure as described assumes that a card deck is being used, the same procedure could, of course, be done at an interactive terminal.) On the card marked "A" the user enters the identifier for his geometri definition file (e.g., GEODEF, ID=CAXX); on the card marked "B" the user must enter the identifier for his geometry file (e.g., GEOM, ID=CAXX.)

THE SOLIDGEN INPUT DECK

The general format of the SOLIDGEN Input Deck is shown in Table 1. The components of the SOLIDGEN Input Deck marked "3" and "4" are described in detail in the paragraphs that follow.

Global Parameters

The Global Parameters, specified on two cards, are intended for use when the generated model is to be analyzed by NASTRAN. Each parameter is intended, as shown in Table 2, to fill in one of the fields on each NASTRAN input data card[5,6] of a specific type which appears in the generated model. Table 3 shows the format of the two cards used to specify the Global Parameters. If the generated model is intended for a finite element analysis program other than NASTRAN, the two cards are still required, but should be left blank.

TABLE 1 - GENERAL FORMAT FOR SOLIDGEN INPUT DECK

1 As many cards as user wishes; contents as user wishes; these cards get "echoed" (reproduced) on the output listing from the line printer and on the file DATA

2 One card with BEGIN BULK starting in column 1

3 Global Parameters; two cards

4 Input Sections; may occur in any order, except Input Section 1 must come first

5 One card with END INPUT starting in column 1

6 As many cards as user wishes; contents as user wishes; these cards get echoed (reproduced) on the output listing from the line printer and on the file DATA

7 One card with ENDDATA starting in column 1

TABLE 2 - GLOBAL PARAMETERS

Parameter	NASTRAN Input Data Card on Which Parameter Appears
CP CD PS	GRID
ID1 ID2 MID	CIS3D8 CIS3D20
PID	CIHEX1 CIHEX2 CIHEX3

TABLE 3 - FORMAT OF GLOBAL PARAMETERS

Parameter	Placement on Global Parameters Cards	
	Card	Field (Eight Columns, *Alphanumeric*)
CP	1	3
CD	1	7
PS	1	8
ID1	2	1
ID2	2	2
MID	2	3
PID	2	4

Input Sections

The Input Sections may be placed in any order, except that Input Section 1 must come first. The information contained in the Input Sections may be placed anywhere on the cards which make up the Input Sections with the following restrictions:

* The data fields (i.e., words and/or parameters) in each Input Section must appear in the sequence prescribed for that Input Section.

* On each card any two consecutive data fields must be separated by at least one blank column.

If an Input Section is marked as "reserved for future use," it means that coding of that Input Section is in progress.

Input Section 1. Input Section 1 specifies how many key reference surfaces belong to each of the three key reference surface families, i.e., N_α, N_β, and N_γ, the number of key reference surfaces in the key α-, β-, and γ-reference surface families, respectively.

Input Section 1 must contain two cards. The first card must have the word "KEY." The second card must contain N_α, N_β, and N_γ.

Input Section 2. Input Section 2 specifies the number of midside points to be used along each zone edge, i.e., M_1, M_2, and M_3, where

M_i = Number of midside points to be used along each Type i zone edge (i = 1, 2, 3).

Input Section 2 may be omitted. If it is omitted, M_1, M_2, and M_3 will all be set to the default value of 2.

If Input Section 2 is included, it must contain two cards. The first card must have the words "MIDSIDE POINTS." The second card must contain M_1, M_2, and M_3.

The three parameters are currently under the following restrictions:

1. $M_1 = M_2 = M_3$
2. $M_i = 0, 1, \text{ or } 2.$

Input Section 3. Input Section 3 specifies the format of the generated elements. One of the following formats may be chosen:

* General Connection Element
* CIHEX1
* CIHEX2
* CIHEX3
* CIS3D8
* CIS3D20
* CHEXA1
* CHEXA2

Input Section 3 must contain at least two cards; if the general connection element is chosen, a third card must be included. The first card must have the words "GENERATED ELEMENT FORMAT." The second card must have one word which specifies the element format ("GENERAL" if the general connection element is desired). If the general connection element has been chosen, a third card which specifies the number of midside nodes to be generated along each element edge, must contain D_1, D_2, and D_3, where

D_i = Number of midside nodes to be generated along each Type i element edge (i = 1, 2, 3).

Input Section 4. Input Section 4 specifies the number of interior reference surfaces that are to lie between each two adjacent key reference surfaces, i.e., $I_{i,j}$, where $I_{i,j}$ specifies the number of interior reference surfaces that are to lie between K(i,j) and K(i,j+1).

Input Section 4 must contain three groups of cards, each of which must specify the values of $I_{i,j}$ for a specific reference surface family. The three groups may be placed in any order.

The first card of the group which describes the interior α-reference surfaces must contain the words "INTERIOR ALPHA." The other cards must contain the following parameters:

$$I_{1,j}, \text{ where } j = 1, 2, \ldots, N_{\alpha}-1.$$

The first card of the group which describes the interior β-reference surfaces must contain the words "INTERIOR BETA." The other cards must contain the following parameters:

$$I_{2,j}, \text{ where } j = 1, 2, \ldots, N_{\beta}-1.$$

The first card of the group which describes the interior γ-reference surfaces must contain the words "INTERIOR GAMMA." The other cards must contain the following parameters:

$$I_{3,j}, \text{ where } j = 1, 2, \ldots, N_{\gamma}-1.$$

Input Section 5. Input Section 5 specifies which of the zones formed by the network of key reference surfaces are occupied (used for the model) and assigns a zone number to each zone.

The first card of Input Section 5 must have the words "START ZONES." The last card of Input Section 5 must be either a blank card or a card with the words "END SECTION." The other cards of Input Section 5 ribe and label the occupied zones; each such card describes and labels one zone. The card which specifies that the zone bounded by K(1,i), K(1,i+1), K(2,j), K(2,j+1), K(3,k), and K(3,k+1) is occupied and is to be called "Zone N" must contain N, i, j, and k.

Input Section 6. Input Section 6 describes the key reference surfaces, i.e., associates each zone face needed by the model with one of the GPRIME surfaces whose descriptions reside in the geometry file.

The first card of Input Section 6 must have the words "START KEY." The rest of Input Section 6 consists of three groups of cards, each group describing a key reference surface family. The three groups may be placed in any order. I, which indicates the key reference surface family being described by a group, is defined as follows: I = 1, 2, or 3 indicates that the group describes the key α-, β-, or γ-reference surface family, respectively.

The first card of each group must contain one of the following pairs of words:

START ALPHA when I = 1

START BETA when I = 2

START GAMMA when I = 3

The last card of each group must either be blank or have the words "END FAMILY." The rest of each group consists of groups of cards (as many as needed), each of which is used for associating one or more zone faces of a key reference surface with a GPRIME surface. Each such group of cards is called an "Associator."

The first card of each Associator must contain the following parameters: N (an integer), M (an integer), GN (a character string), and NZ (an integer). These parameters are described below.

N indicates that all the zone faces being described by the Associator belong to K(I,N).

M is the mode in which the Associator is being used. If M = 1, all of K(I,N) (entire key reference surface) is to be associated with GN (GPRIME surface), NZ is not needed, and the Associator should consist of only one card, the card which contains N, M, and GN. If M = 2 or M = 3, the rest of the Associator (i.e., those cards of the Associator which follow the first card) should consist of one or more cards which are used to specify a group of zone faces, each of which belongs to K(I,N); each such group of zone faces will be referred to as "G."

The cards of the Associator which follow the first card and which specify G will be referred to as a "Zone Face Group Card Set." (NZ is a parameter associated with each Zone Face Group Card Set.)

If M = 2, G is to be associated with GN (GPRIME surface). IF M = 3, the complement of G, i.e., those zone faces of K(I,N) which do not belong to G, is to be associated with GN.

Each zone face that belongs to G is designated by naming one or more occupied zones to which it belongs. If the zone face belongs to only one occupied zone, that zone must be named. If the zone face belongs to two occupied zones, one or both of those zones may be named.

GN is the name of the GPRIME surface to be associated with all or part of K(I,N).

NZ is the total number of zones named in each Zone Face Group Card Set.

Input Section 7. Reserved for future use.

Input Section 8. This input section is used for describing constraints that are to be applied to grid points which lie on certain zone faces or key reference surfaces, as specified by the user.

The first card of Input Section 8 should have the word "CONSTRAINTS." This is followed by three or fewer groups of cards. Each of these groups describes constraints that are to be applied to zone faces or key reference surfaces belonging to one of the three key reference surface families. These groups may be placed in any order. If no constraints are to be applied to zone faces or key reference surfaces of a family, the group for that family is omitted. The last card of Input Section 8 should be a blank card.

Each group which describes constraints for one of the key reference surface families should begin with a card that contains one of the following three words:

ALPHA

BETA

GAMMA

Each group is ended with a blank card. The rest of each group specifies constraints for the key reference surface family and may contain as many cards as are needed. These cards occur either singly or in pairs, as follows. If an entire key reference surface is to be constrained, one card is used as follows:

1. Surface number (an integer)
2. The word "ALL" (text)
3. Set identification (an integer)
4. Coordinate system for displacements specification (8-character field)
5. Permanent single point constraints specification (field of one to six characters)

Items 4 and 5 are needed only if they were not specified previously. If only part of a key reference surface is to be constrained, two cards are used as follows:

First Card -

1. Surface number (an integer)
2. The word "PART" (text)
3. Set identification (an integer)
4. Coordinate system for displacements specification (8-character field)
5. Permanent single point constraints specification (field of one to six characters)

Items 4 and 5 are needed only if they were not specified previously.

Second Card -

Zone numbers (integers) (as many as needed). Each zone number specifies one zone face as follows: The zone face belongs to the zone whose zone number is given.

Input Section 9. This Input Section is used for assigning material properties to zones, as specified by the user.

The first card of Input Section 9 should have the following text:

MATERIAL PROPERTIES

The last card should be a blank card. The rest of Input Section 9 consists of pairs of cards. Each such pair of cards associates one or more zones with a specified material. The first card of each pair contains the following:

ALL (text)
(meaning all zones of the model)

or

ZONE n (text, followed by one integer)
(meaning one zone)

or

ZONES n_1 n_2... (text, followed by integers)
(meaning zones specified)

The second card of each pair contains either the integer MID or the integer PID, where PID is the identification number of a PIHEX property card (for CIHEX1, CIHEX2, and CIHEX3 elements) and MID is the material identification number of a MAT1 material property card (for CHEXA1 and CHEXA2 elements). (MAT1 cards are placed in the SOLIDGEN Input Deck before the BEGIN BULK card.)

Input Section 10. Input Section 10 specifies whether or not surface correction is to be applied to the grid points.

Input Section 10 may be omitted. If it is omitted, surface correction will be performed.

If Input Section 10 is included, it must contain two cards. The first card must have the words "SURFACE CORRECTION." If surface correction is desired, the second card should contain the word "YES." If surface correction is not desired, the second card should contain the word "NO."

Input Section 11. This input section is used for describing pressure loads that are to be applied to zone faces or key reference surfaces, as specified by the user.

The first card of Input Section 11 should have the text "PRESSURE LOADS." This is followed by three or fewer groups of cards. Each of these groups describes pressure loads that are to be applied to zone faces or key reference surfaces belonging to one of the three key reference surface families. These groups may be placed in any order. If no pressure loads are to be applied to zone faces or key reference surfaces of a family, the group for that family is omitted. The last card of Input Section 11 should be a blank card.

Each group which describes pressure loads for one of the key reference surface families should begin with a card that contains one of the following three words:

ALPHA

BETA

GAMMA

Each group is ended with a blank card. The rest of each group specifies pressure loads for the key reference surface family and may contain as many cards as are needed. These cards occur either singly or in pairs, which will now be described. If an entire key reference surface is to be pressure-loaded, one card is used as follows:

1. Surface number (an integer)
2. The word "ALL" (text)
3. Set identification (an integer)
4. Pressure (one real number)

Item 3 is needed only if it was not specified previously. If only part of a key reference surface is to be pressure-loaded, two cards are used as follows:

First Card -

1. Surface number (an integer)
2. The word "PART" (text)
3. Set identification (an integer)
4. Pressure (one real number)

Item 4 is needed only if it was not specified previously.

Second Card -

Zone numbers (integers) (as many as needed). Each zone number specifies one zone face as follows: The zone face belongs to the zone whose zone number is given.

Input Section 12. Input Section 12 specifies values for N_G and N_E, the two parameters needed when the model currently being generated is to be used as part of a larger model, where

N_G = Integer to be added to each grid point number

and

N_E = Integer to be added to each element identifier

If the model currently being generated is not to be combined with any other models, Input Section 12 is omitted.

When it is used, Input Section 12 must contain five cards. The first card contains the word "COMPONENT." The remaining cards consist of two pairs, which may be placed in any order. One of those pairs consists of the following cards:

* A card which contains the word "GRID."
* A card which contains the value of N_G (an integer)

The other pair consists of the following cards:

* A card which contains the word "ELEMENT."
* A card which contains the value of N_E (an integer)

CONTROL CARDS FOR MODEL GENERATION RUN

The control cards for running SOLIDGEN are shown in Figure 14. On the card marked "*" the user must enter the identifier for his geometry file (e.g., GEOM, ID=CAXX).

```
C         JOB CARD
* ——→ATTACH,UMFX,GEOMETRY FILE,MR=1.
      COPYBF,UMFX,UMF.
      RETURN,UMFX.
      REWIND,UMF.
      ATTACH,SOLIDGN,ID=CARK.
      SOLIDGN.
```

Figure 14 - Control Cards for Running SOLIDGEN

WORK IN PROGRESS

SOME HELPFUL CONCEPTS

The following concepts are expected to be implemented in future versions of SOLIDGEN.

Gluing

Sometimes a procedure referred to as "gluing" will simplify the modeling of a complicated object. This procedure will be defined in general terms and then illustrated by an example.

"Gluing" is defined in general terms as follows:

1. Cut into the interior of the object, thus creating a bounded surface which lies (except possibly for its boundary) entirely inside the object.

2. Create two distinct zone faces both of which are described by this bounded surface. That is, define the key reference surfaces

so that two distinct zone faces are associated with the same GPRIME surface and have coinciding corner points and coinciding zone edges.

3. In the generated model, each grid point which lies on one of the zone faces must coincide with a grid point which lies on the other zone face. Form a single grid point from each such pair of grid points by replacing all references to one of the grid point numbers with a reference to the other grid point number, thus "gluing" the two zone faces together.

An object to be modeled is shown in Figure 15. Figures 16 and 17 show how the object might be subdivided into zones if it were to be modeled without the aid of gluing and with the aid of gluing, respectively. The topological model of the object modeled with the aid of gluing is shown in Figure 18. The topological model without gluing would require 9 zones in a 3 x 3 arrangement with the middle zone declared vacant. The following pair of zone faces will be glued together:

(1) The zone face which belongs to Zone 1 and belongs to K(1,6)

(2) The zone face which belongs to Zone 5 and belongs to K(1,1).

Most users would probably find the modeling shown in Figure 17 (gluing) much easier to devise than the modeling shown in Figure 16 (no gluing). Note also that Zones 1, 3, 5, and 7 of the model made without gluing (Figure 16) might cause undesirable elements to be generated because of their sharply angled corners at the edge of the hole in the object.

Zone Defining Point Validation Mode

Finding the zone defining points (i.e., the corner points and midside points) is a crucial part of SOLIDGEN and can sometimes be difficult due to errors in the GPRIME surface definitions (e.g., three GPRIME surfaces do not properly intersect

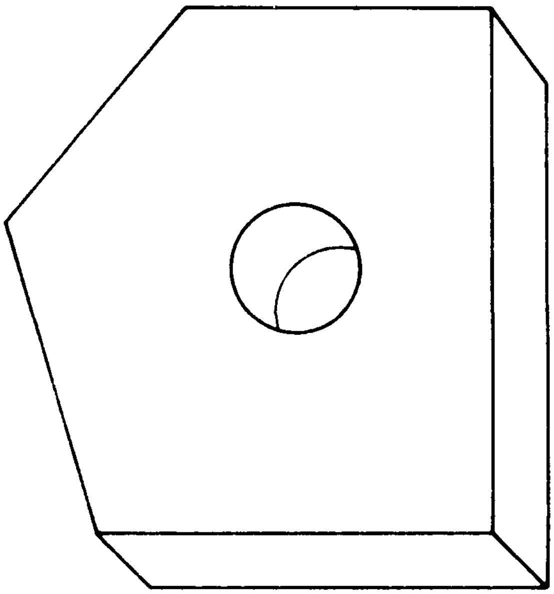


Figure 15 - Object to be Modeled with Aid of Gluing

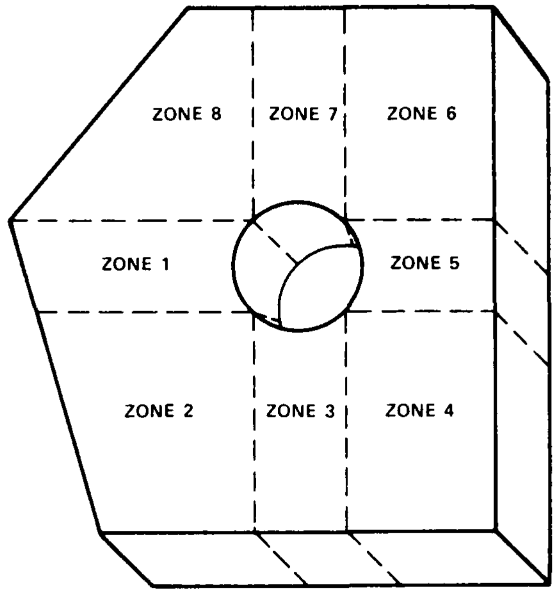


Figure 16 - Subdivision of Object into Zones without Gluing

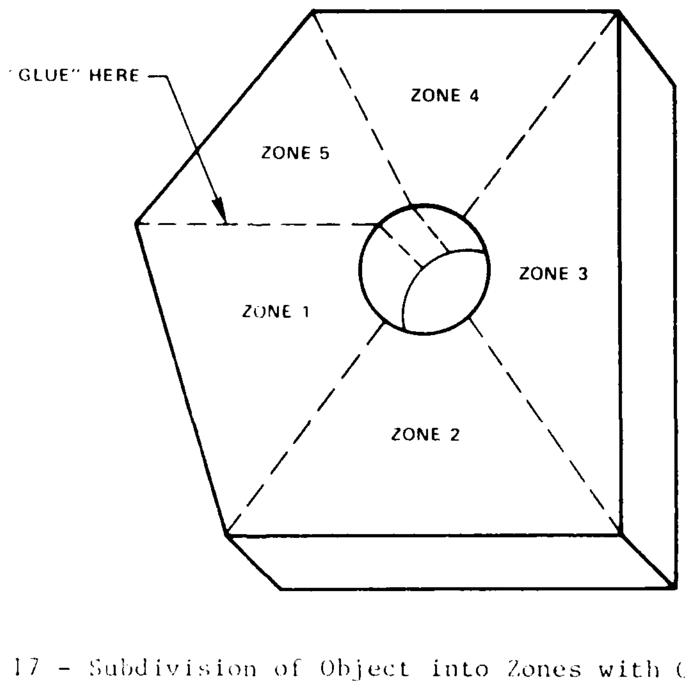


Figure 17 - Subdivision of Object into Zones with Gluing

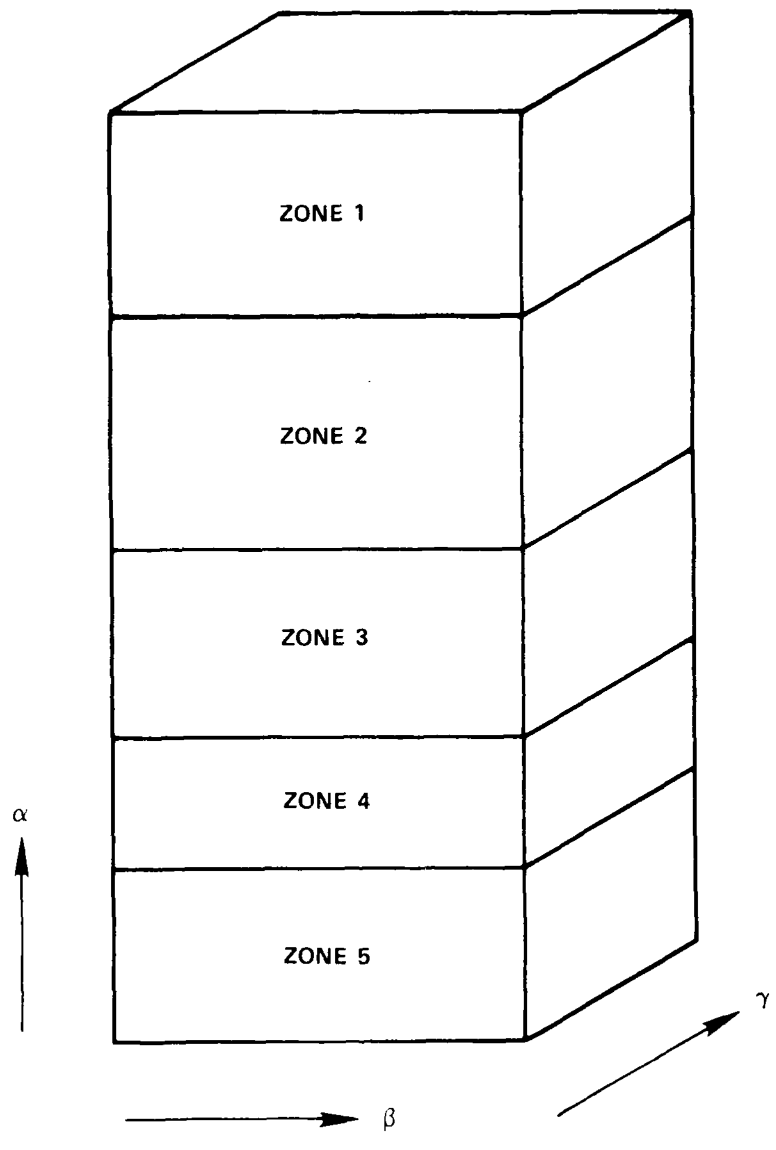


Figure 18 - Topological Model of Object Modeled with Aid of Gluing

to form a point) or to errors in the SOLIDGEN Input Deck (e.g., a zone face has been incorrectly associated with a GPRIME surface). Sometimes for a given problem more than one such difficulty can occur. SOLIDGEN, when running in its normal mode, will stop each time it encounters such a difficulty.

In the "zone defining point validation mode," SOLIDGEN will attempt only to find zone defining points; all other operations will be omitted. In this mode, instead of halting each time it encounters difficulty in finding a zone defining point, SOLIDGEN will print a diagnostic message and continue to attempt to find zone defining points. Using this mode will enable the SOLIDGEN user to quickly determine (i.e., in one pass) exactly which zone defining points will cause difficulty.

Helper Surfaces

Consider two natural zone faces which have a zone edge in common and lie in different key reference surfaces. If two such zone faces are described by the same GPRIME surface and the common zone edge does not belong to any other zone face, additional information will be needed to describe the common zone edge. An example of such a situation is shown in Figure 19, in which the zone face belonging to K(1,2) and the zone face belonging to K(2,1) are both described by the same surface, a right circular cylinder. If a "helper surface" (an additional surface which intersects the original GPRIME surface) is specified, the zone edge will be properly defined.

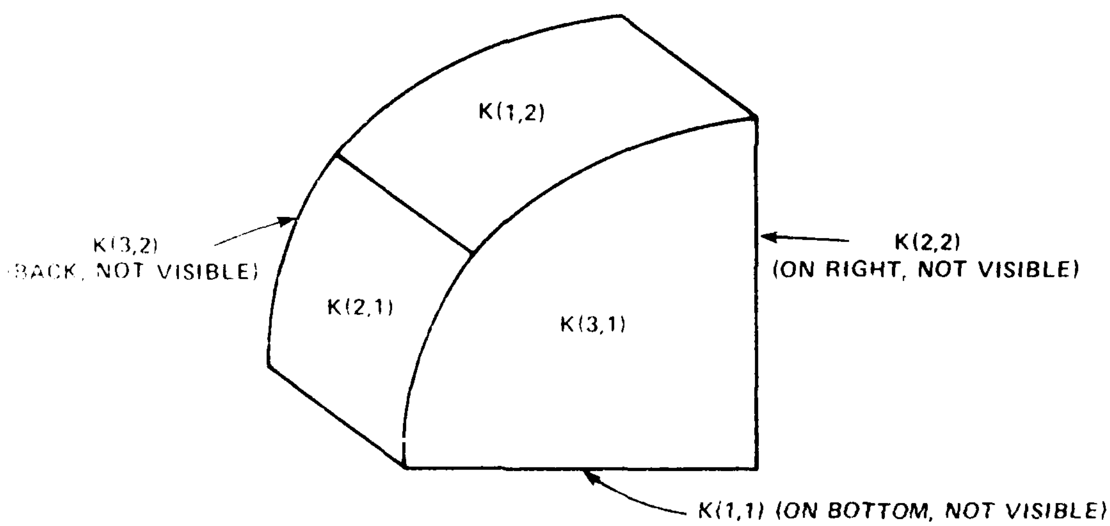


Figure 19 - Example of Need for Helper Surface

FUTURE FEATURES

The following features are expected to be included in future versions of SOLIDGEN:

* Automatically glue together two specified zone faces
* Zone defining point validation mode
* Associate properties (e.g., material properties) with specified zones
* Associate properties (e.g., loads and boundary conditions) with specified key reference surfaces
* Provide helpful topological information about the model, for example:
    a. Tell which grid points are located on a specified corner point, zone edge, zone face, or key reference surface
    b. Tell which elements belong to a specified zone
* Allow selected zone defining points to be explicitly specified
* Automatically detect the existence of a "bad" zone, i.e., a zone which will cause the generation of undesirably shaped elements
* Automatically detect a violation of the requirement that the α-, β-, and γ-axes form a right-handed system
* Allow groups of zones to be used during the description of a model, e.g., to specify a group of zone faces
* Allow the user to specify that the model is to lie within a given volume
* Allow the use of degenerate zones, e.g., wedges
* Allow the use of a helper surface when needed to properly define a zone edge.

APPENDIX A
SAMPLE PROBLEMS

SAMPLE PROBLEM 1

Figure 20 shows two orthographic views of a globe valve, of which only the housing (stationary part) is to be modeled. Since there are three planes of symmetry, one-eighth of the valve is sufficient for the structural modeling and analysis. To describe the modeling in terms of key reference surfaces and zones, the user must visualize the object as subdivided into zones bounded by a consistently defined set of key reference surfaces. This process does not lend itself to any specific procedure, but the following details of this sample problem are illustrative. Figure 21 shows how one-eighth of the valve would appear and also shows some GPRIME surfaces which will be used for the structural modeling, i.e., for describing the key reference surfaces. The GPRIME surfaces are described in Table 4. (Note that S14 is a constructed GPRIME surface.) A geometric definition file which is consistent with the descriptions of the GPRIME surfaces contained in Table 4 is shown in Figure 22.

The user then defines the model topologically; that is, he must

1. assign the three key reference surface families with respect to the GPRIME surfaces used for modeling the object;
2. specify which zones in the network of key reference surfaces are occupied (used for the model); and
3. label (assign a number to) each occupied zone.

Although it is not absolutely necessary to make a drawing of the topological model like the one in Figure 23, such a drawing can help to visualize the problem. The constructed zone faces are listed in Table 5.

Finally, the user specifies the topological model, describes the key reference surfaces, and specifies other parameters needed for the model generation by making up a SOLIDGEN Input Deck. A SOLIDGEN Input Deck for this sample problem is shown in Figure 24 and two views of the generated model are shown in Figure 25.

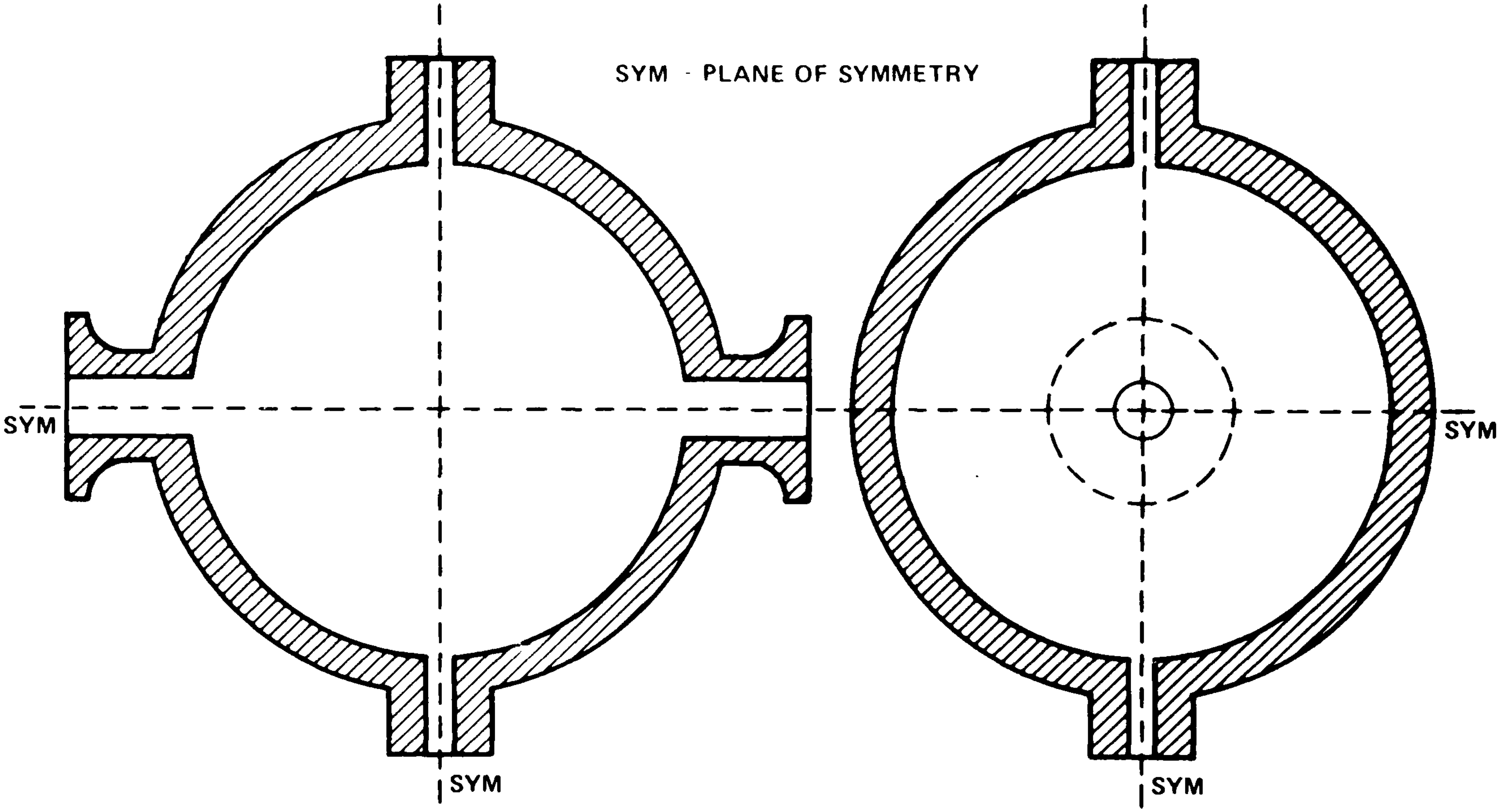


Figure 20 - Two Orthographic Views of Globe Valve, Sample Problem 1

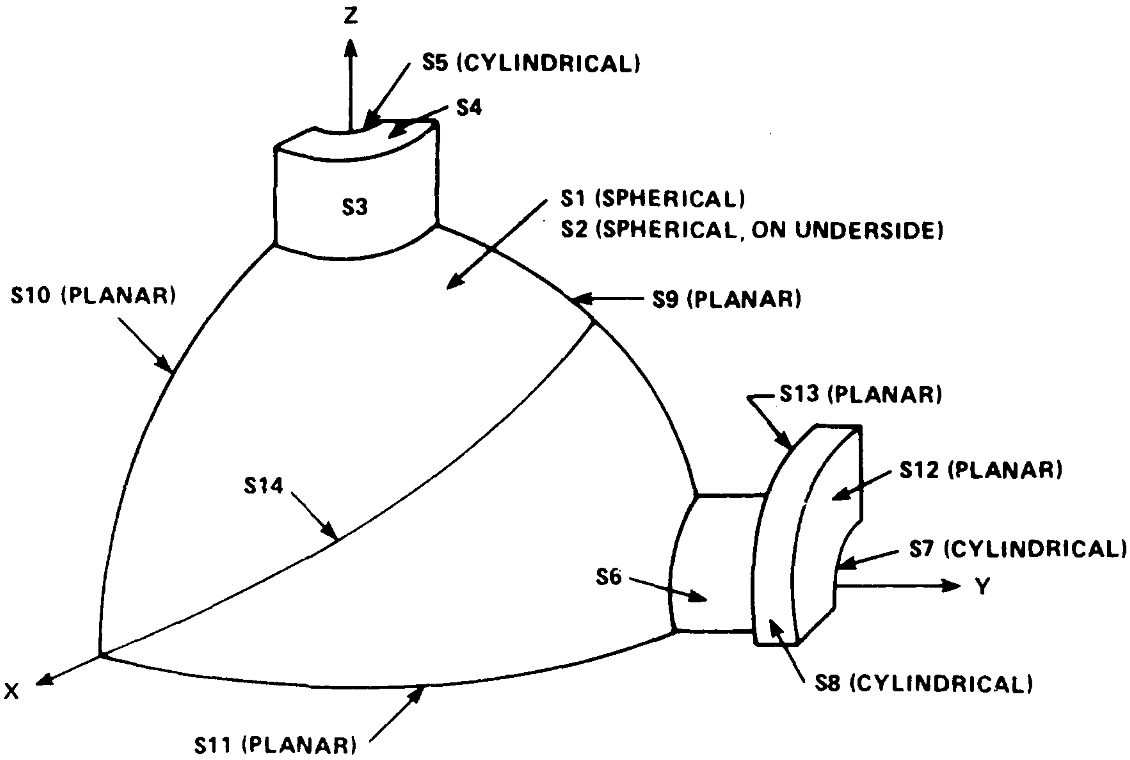


Figure 21 - Isometric View of One-Eighth of Globe Valve,
Sample Problem 1

TABLE 4 - GPRIME SURFACES, SAMPLE PROBLEM 1

Surface	Description
S1	Part of sphere whose center is at origin
S2	Part of sphere whose center is at origin, radius less than radius of sphere for S1
S3	Part of right circular cylinder whose axis is z-axis
S4	Part of plane of constant z
S5	Part of right circular cylinder whose axis is z-axis, radius less than radius of cylinder for S3
S6	Part of right circular cylinder whose axis is y-axis
S7	Part of right circular cylinder whose axis is y-axis, radius less than radius of cylinder for S6
S8	Part of right circular cylinder whose axis is y-axis, radius greater than radius of cylinder for S6
S9	Part of plane $x = 0$
S10	Part of plane $y = 0$
S11	Part of plane $z = 0$
S12	Part of plane of constant y
S13	Part of plane of constant y
S14	Part of plane which contains x-axis and which makes a 45° angle with the plane $z = 0$

```
INITIAL
PRINT
BATCH
COMMENT. GLOBE VALVE   MODELED WITHIN OCTANT
P0,POI,0,0,0
S4,PLANE,6,0,5,0,5,Z
S12,PLANE,6.5,0,5,0,5,Y
S13,PLANE,5,0,5,0,5,Y
S9,PLANE,0,0,9,0,9,X
S10,PLANE,0,0,9,0,9,Y
S11,PLANE,0,0,9,0,9,Z
COMMENT.
P10,POINT,4,0,0
P30,POINT,0,0,4
C20,ARC,P0,P30,P10,CENTER
S2,ZSURFACE,C20,-90
COMMENT.
P11,POINT,4.5,0,0
P31,POINT,0,0,4.5
C21,ARC,P0,P31,P11,CENTER
S1,ZSURFACE,C21,-90
COMMENT.
P41,POINT,1.5,0,6
P40,POINT,1.5,0,0
C03,LINE,P41,P40
S3,ZSURFACE,C03,-90
COMMENT.
P51,POINT,1,0,6
P50,POINT,1,0,0
C05,LINE,P51,P50
S5,ZSURFACE,C05,-90
COMMENT.
P61,POINT,0,8,1.5
P60,POINT,0,0,1.5
C06,LINE,P61,P60
S6,YSURFACE,C06,-90
COMMENT.
P71,POINT,0,8,1
P70,POINT,0,0,1
C07,LINE,P71,P70
S7,YSURFACE,C07,-90
COMMENT.
P81,POINT,0,8,2.5
P80,POINT,0,0,2.5
C08,LINE,P81,P80
S8,YSURFACE,C08,-90
COMMENT.
OT1,ORIENT,45,0,0,P0
S14,S10,OT1
END
```

Figure 22 Geometric Definition File, Sample Problem 1

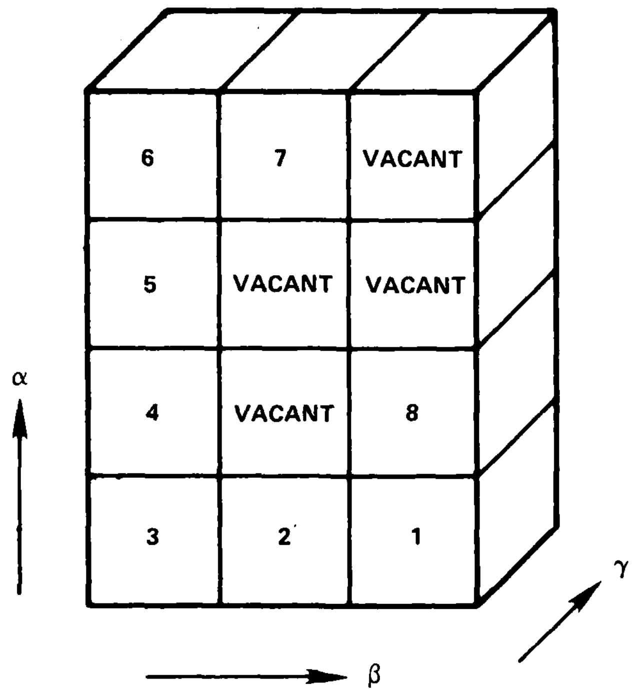


Figure 23 - Topological Model, Sample Problem 1, Showing Occupied Zones

TABLE 5 - CONSTRUCTED ZONE FACES, SAMPLE PROBLEM 1

K(i,j), Key Reference Surface to which Zone Faces Belong		Zones to which Zone Faces Belong
i	j	
1	2	1 and 3
1	3	4
1	4	5
2	2	2 and 7
2	3	1

```
                    SAMPLE PROBLEM 1                    GLOBE VALVE
BEGIN BULK
                                       1          1
KEY
           5            4             2
GENERATED ELEMENT FORMAT
CIHEX2
INTERIOR ALPHA
     0     2     2      0
INTERIOR BETA
     0     1     0
INTERIOR GAMMA
     3
START ZONES
           1            1            3            1
           2            1            2            1
           3            1            1            1
           4            2            1            1
           5            3            1            1
           6            4            1            1
           7            4            2            1
           8            2            3            1

START KEY
START ALPHA
           1            1 S7
           2            1 S6
           3            2 S8                   1
     8
           3            2 S14                  2
     4     5
           4            1 S3
           5            1 S5

START BETA
           1            1 S2
           2            1 S1
           3            2 S13                  3
     1     8     2
           3            2 S4                   1
     7
           4            1 S12

START GAMMA
           1            2 S11                  5
     8     1     2      3     4
           1            2 S10                  3
     5     6     7
           2            1 S9

        CONSTRAINTS
           GAMMA
  1       PART     1       1       2
           7    6    5
1      PART      2      1      3
     4    3    2    1    8
2      ALL      3      1      1


PRESSURE LOADS
ALPHA
       1    ALL    1    15.0
       5    ALL    1

BETA
     1    ALL    1

   MATERIAL PROPERTIES
        ALL
        1

END INPUT
ENDDATA
```

Figure 24 - SOLIDGEN Input Deck, Sample Problem 1

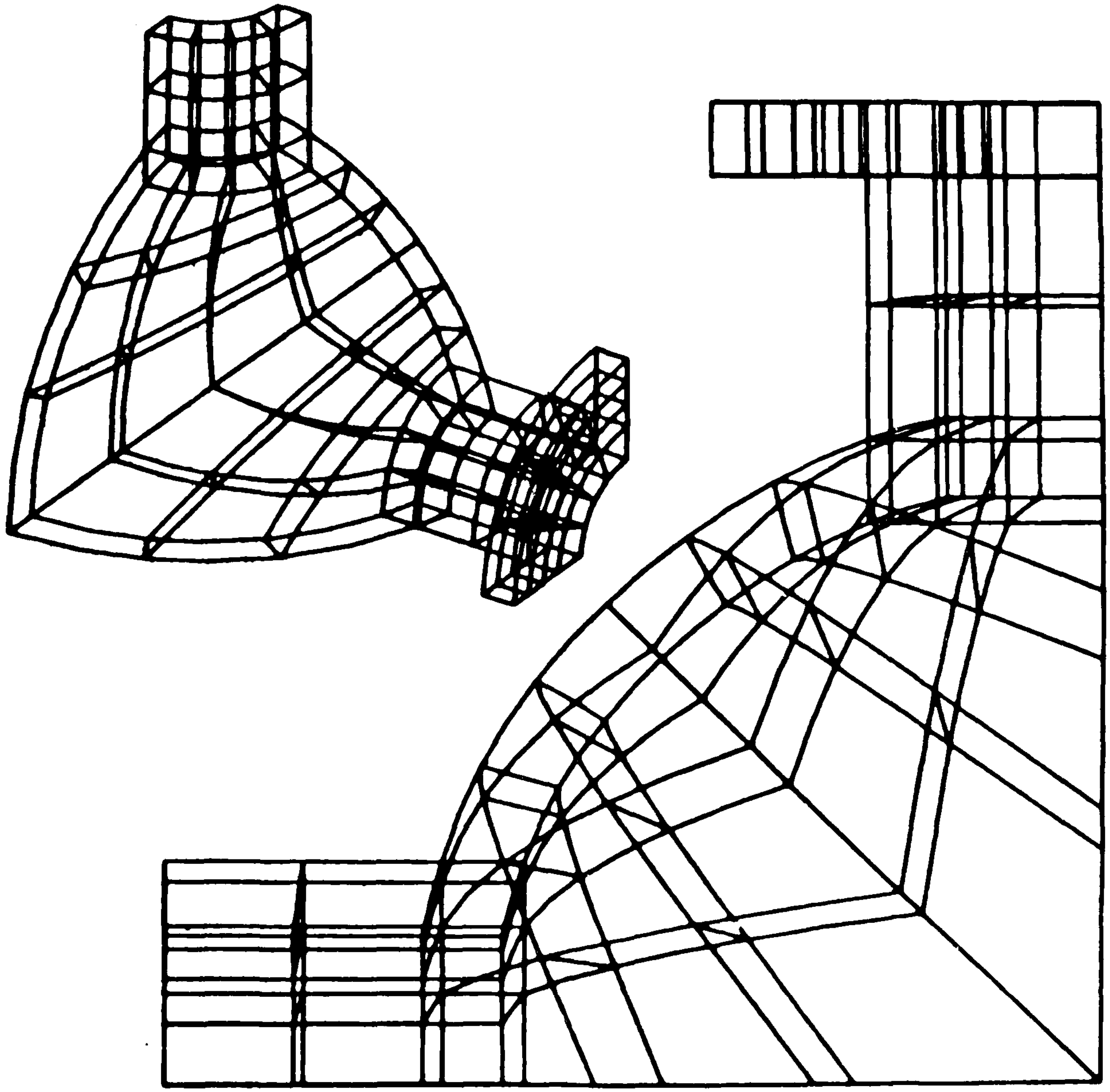


Figure 25 - Generated Model, Sample Problem 1

SAMPLE PROBLEM 2

Figure 26 shows two orthographic views of a machine part. Since there are two planes of symmetry, one-fourth of the part is sufficient for the structural modeling and analysis. Figure 26 also shows some GPRIME surfaces which will be used for the structural modeling, i.e., for describing the key reference surfaces; the GPRIME surfaces are described in Table 6. If in Table 6 the description of a GPRIME surface does not specify the limits of a particular coordinate, that coordinate has a range which extends over the entire object being modeled. Note that S11, S12, S13, and S14 are constructed GPRIME surfaces. A geometric definition file which is consistent with the descriptions of the GPRIME surfaces in Table 6 is shown in Figure 27.

Figure 28 shows the topological model for this problem. Note that K(2,2) and K(2,3) are constructed key reference surfaces. The constructed zone faces are listed in Table 7.

A SOLIDGEN Input Deck which could be used for this problem is shown in Figure 29. Two views of the generated model are shown in Figure 30.

It is not unusual to have difficulty in properly defining the GPRIME surfaces (and in creating the geometric definition file) if the model has not been adequately visualized. Consider, for example, the plane y = 0 (a plane of symmetry), which is needed for K(2,1) and K(2,5). Although it seems obvious and natural to represent that plane by one GPRIME surface whose range extends over the entire object, use of such a GPRIME surface would cause several violations of Requirement 1 (Corner Point Uniqueness Requirement; see Appendix C). Therefore, two GPRIME surfaces, S61 and S62, were used instead.

Sometimes, instead of subdividing a GPRIME surface into two or more GPRIME surfaces, the user needs only to limit its extent. For example, because using an S10 with too large a range on x (e.g., a range on x which extends over the entire object) would have caused several violations of Requirement 1, S10 was limited so that $x \leq a_2$.

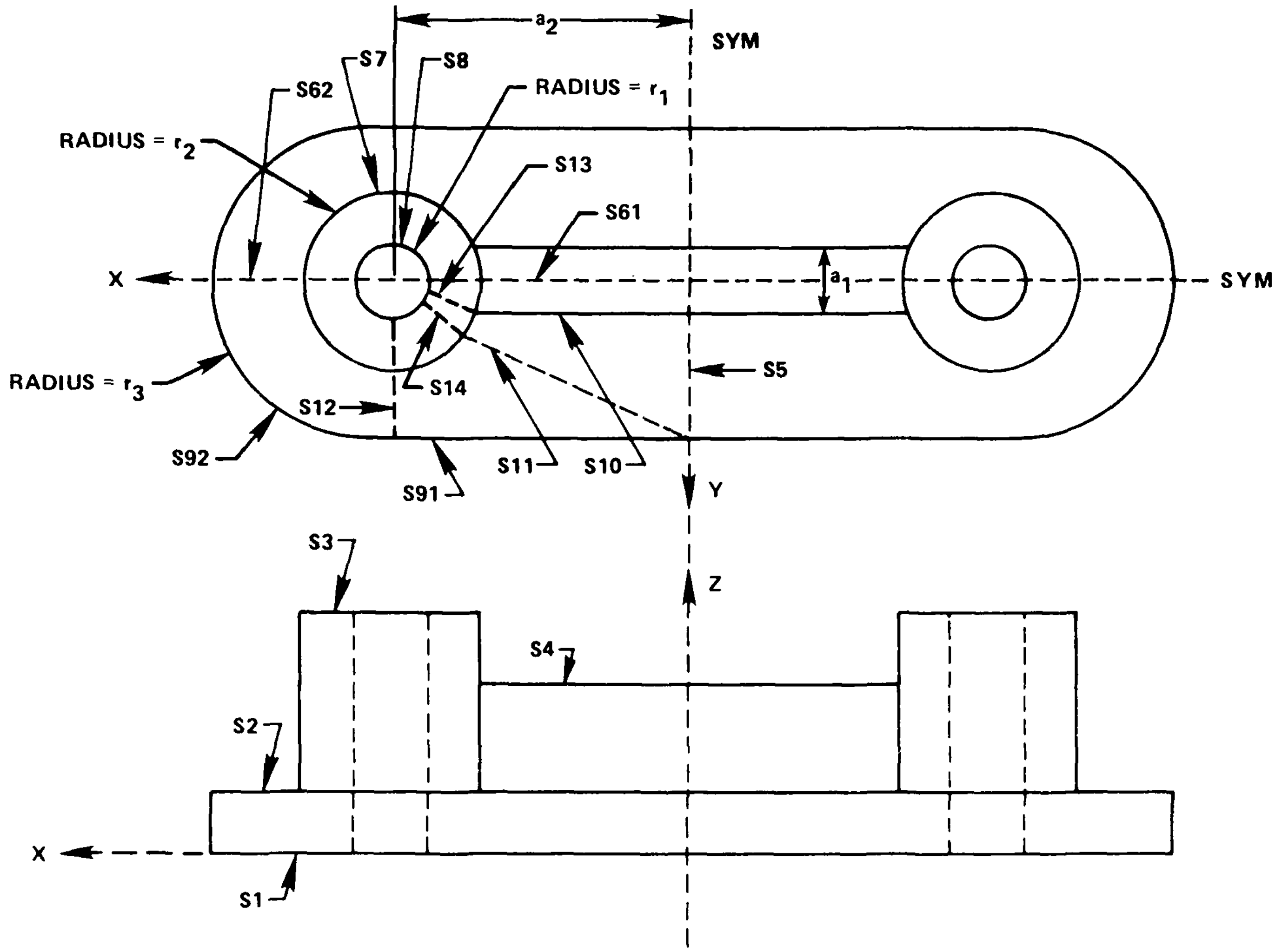


Figure 26 - Two Orthographic Views of Object, Sample Problem 2

TABLE 6 - GPRIME SURFACES, SAMPLE PROBLEM 2

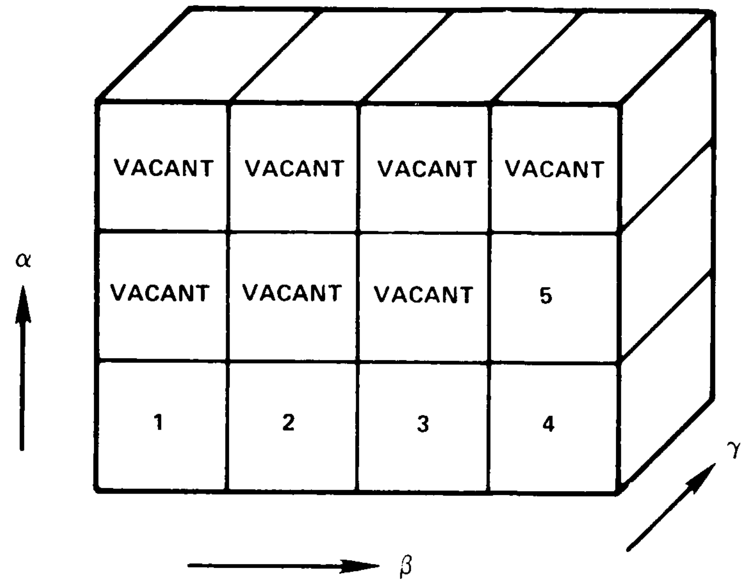
Surface	Description
S1	Part of plane of constant z
S2	Part of plane of constant z
S3	Part of plane of constant z
S4	Part of plane of constant z
S5	Part of plane $x = 0$
S61	Part of plane $y = 0$; limited by planes $x = 0$ and $x = a_2$
S62	S61 translated in the x direction by a_2
S7	Part of right circular cylinder whose axis is the line parallel to the z-axis for which $x = a_2$ and $y = 0$; radius is r_2
S8	Part of right circular cylinder whose axis is the line parallel to the z-axis for which $x = a_2$ and $y = 0$; radius is r_1
S91	Part of plane $y = r_3$; limited by planes $x = 0$ and $x = a_2$
S92	Part of right circular cylinder whose axis is the line parallel to the z-axis for which $x = a_2$ and $y = 0$; radius is r_3; projection on the plane $z = 0$ is a 90° arc
S10	Part of plane $y = a_1/2$; limited by planes $x = 0$ and $x = a_2$
S11	Part of plane parallel to the z-axis; contains the line parallel to the z-axis for which $x = 0$ and $y = r_3$; also contains the line parallel to the z-axis for which $x = a_2$ and $y = a_1/2$; limited in extent by the aforementioned two lines
S12	Part of plane $x = a_2$; limited by planes $y = 0$ and $y = r_3$
S13	Part of plane parallel to the z-axis; contains the line parallel to the z-axis for which $x = a_2$ and $y = 0$; also contains the line formed by the intersection of S10 and S7; limited in extent by the aforementioned two lines
S14	Part of plane parallel to the z-axis; contains the line parallel to the z-axis for which $x = a_2$ and $y = 0$; also contains the line formed by the intersection of S11 and S7; limited in extent by the aforementioned two lines

```
INIT
PRINT
BATCH
SCR,L
DRA,N
COMMENT.  SC32    Z VALUE FOR S2
SC32,SCA,1
COMMENT.  SC33    Z VALUE FOR S3
SC33,SCA,5
COMMENT.  SC34    Z VALUE FOR S4
SC34,SCA,4
COMMENT.  SC75    MIDDLE RADIUS
SC75,SCA,2
COMMENT.  SC85    SMALL RADIUS
SC85,SCA,1
COMMENT.  SC95    LARGE RADIUS
SC95,SCA,4
COMMENT.  SC101    DISTANCE BETWEEN Y AXIS
COMMENT.           AND CENTER OF CIRCLES
SC101  CA,7
COMME  .  SC404    HALF THICKNESS OF RIB
SC404,SCA,.95
COMMENT.
COMMENT.   ORIENTATION
COMMENT.   TRANSFORMATIONS
P708,POI,SC101,0,0
P909,POI,0,0,SC33
OT1,ORIENT,0,0,0,P708
OT2,ORIENT.0,0,0,P909
P707,POINT,0,SC404,0
OT3,ORIENT,0,C,0,P707
COMMENT.
P818,POI,0,SC95,0
P992,POI,SC101,SC95,0
P993,POI,9,3.464,0
P994,POI,9.828,2.828,0
P995,POI,10.464,2,0
P996,POI,11,0,0
C90,CURVE,0,P818,P992,P992,P993,P994,P995,P996
C91,C90,OT2
S9,SURFACE,C90,C91
```

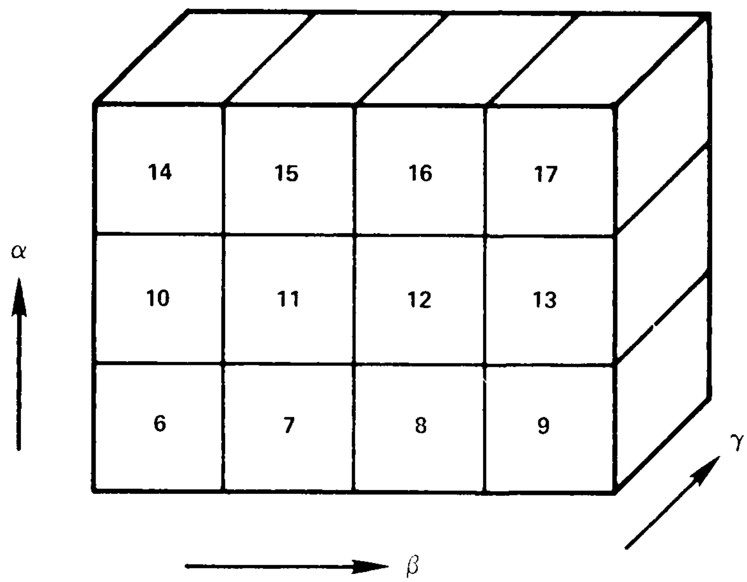
Figure 27 - Geometric Definition File, Sample Problem 2

Figure 27 (Continued)

```
COMMENT.    PLANES
S1,PLANE,0,0,15,0,10,Z
S2,PLANE,SC32,0,15,0,10,Z
S3,PLANE,SC33,0,15,0,10,Z
S4,PLANE,SC34,0,15,0,10,Z
S5,PLANE,0,0,10,0,SC33,X
S6,PLANE,0,0,15,0,SC33,Y
S61,PLANE,0,0,SC101,0,SC33,Y
COMMENT.
P70,POINT,SC75,0,0
P71,POI,SC75,0,SC33
C07,LINE,P70,P71
S75,ZSURFACE,C07,-180
S7,S75,OT1
COMMENT.
P80,POI,SC85,0,0
P81,POI,SC85,0,SC33
C08,LINE,P80,P81
S85,ZSURFACE,C08,-180
S8,S85,OT1
COMMENT.
P710,P707,OT1
C110,LINE,P818,P710
C111,C110,OT2
S11,SURFACE,C111,C110
COMMENT.
S62,S61,OT1
S10,S61,OT3
COMMENT.
P139,INT,S10,S7,S1
C130,LINE,P708,P139
C131,C130,OT2
S13,SURFACE,C130,C131
COMMENT.
P149,INT,S11,S7,S1
C140,LINE,P708,P149
C141,C140,OT2
S14,SURFACE,C140,C141
COMMENT.
C120,LINE,P708,P992
C121,C120,OT2
S12,SURFACE,C120,C121
COMMENT.
C910,LINE,P818,P992
C911,C910,OT2
S91,SURFACE,C910,C911
COMMENT.
C920,ARC,P708,P992,P996,CENTER
C921,C920,OT2
S92,SURFACE,C920,C921
END
```



KEY γ-REFERENCE
SURFACE 1
AT FRONT



KEY γ-REFERENCE
SURFACE 2
AT FRONT

Figure 28 - Topological Model, Sample Problem 2,
Showing Occupied Zones

TABLE 7 - CONSTRUCTED ZONE FACES, SAMPLE PROBLEM 2

K(i,j), Key Reference Surface to which Zone Faces Belong		Zones to which Zone Faces Belong
i	j	
1	2	5, 6, 7, 8, and 9
1	3	10, 11, 12, and 13
2	2	All*
2	3	All*
2	4	3, 8, 12, and 16
3	2	1, 2, 3, 4, and 5

*Means: all zones which have a zone face that belongs to K(i,j).

```
           SAMPLE PROBLEM 2              MACHINE PART
BEGIN BULK

                          1        1
KEY
         4         5          3
GENERATED ELEMENT FORMAT
CIHEX2
INTERIOR ALPHA
    0    1    0
INTERIOR BETA
    1   -1    1    0
INTERIOR GAMMA
    1    0
START ZONES
         1         1         1         1
         2         1         2         1
         3         1         3         1
         4         1         4         1
         5         2         4         1
         6         1         1         2
         7         1         2         2
         8         1         3         2
         9         1         4         2
        10         2         1         2
        11         2         2         2
        12         2         3         2
        13         2         4         2
        14         3         1         2
        15         3         2         2
        16         3         3         2
        17         3         4         2

START KEY
START ALPHA
         1         1 S1
         2         1 S2
         3         1 S4
         4         1 S3

START BETA
         1         1 S62
         2         1 S12
         3         2 S11              2
    2    3
         3         3 S14              1
    2
         4         2 S10              3
    3    4    5
         4         3 S13              2
    4    5
         5         1 S61

START GAMMA
         1         2 S22              1
    1
         1         2 S21              1
    2
         1         3 S5               2
    1    2
         2         1 S7
         3         1 S8

CONSTRAINTS
ALPHA
1   ALL   1   1   3

BETA
1   ALL   2   1   2
5   ALL   2

GAMMA
1   PART   3   1   1
  3   4   5


PRESSURE LOADS
GAMMA
  3   ALL   1   15.0


MATERIAL PROPERTIES
  ALL
   1

END INPUT
ENDDATA
```

Figure 29 - SOLIDGEN Input Deck, Sample Problem 2

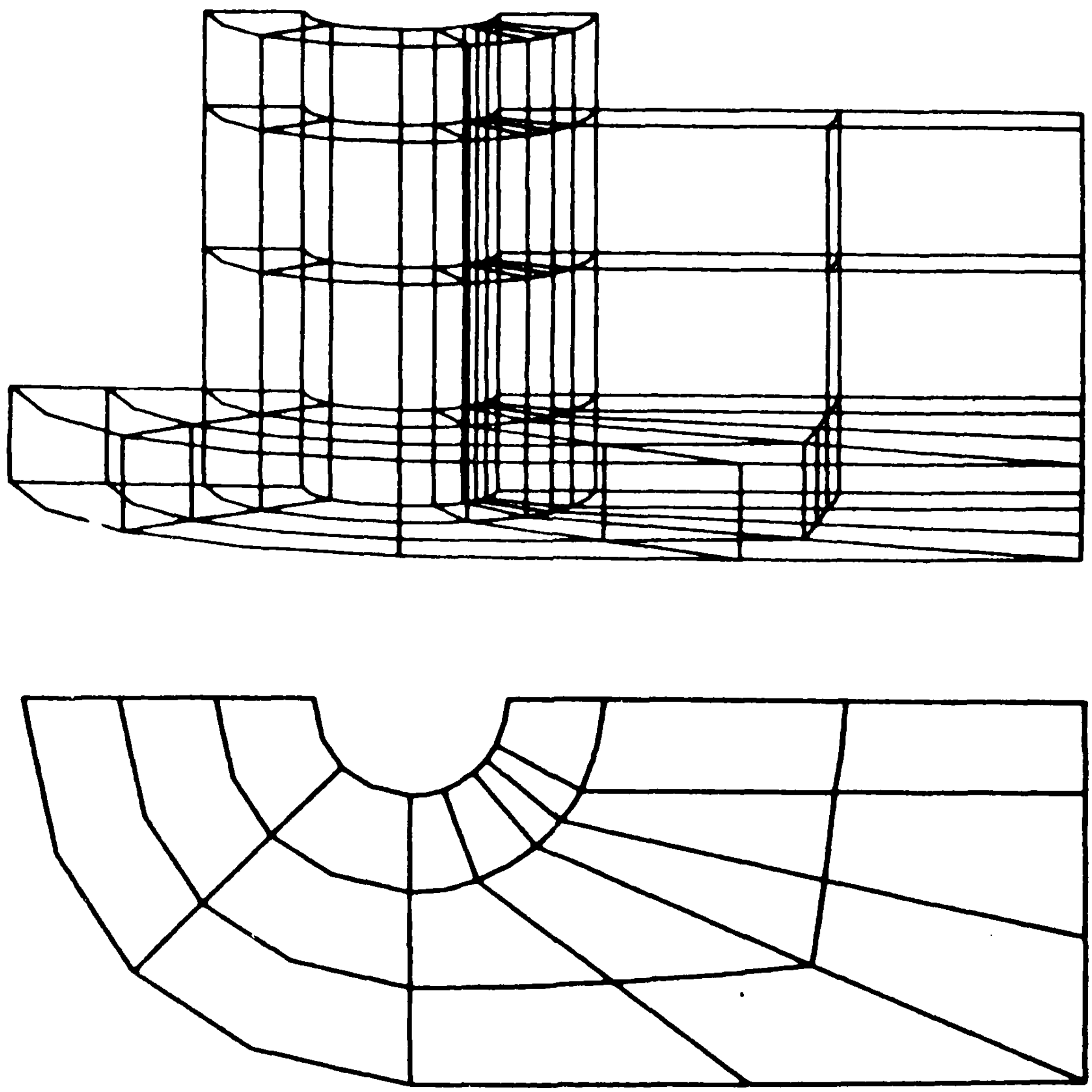


Figure 30 - Generated Model, Sample Problem 2

APPENDIX B

SOME ADDITIONAL CONTROLS OVER SOLIDGEN

Sometimes the storage capacity of certain arrays used in the SOLIDGEN code will need to be temporarily expanded to accommodate a large problem. The user can make such expansions by including two "correction sets" in the deck used for making the computer run in which SOLIDGEN generates the model. The two correction sets run in conjunction with the SOLIDGEN program files so that a temporarily modified version of SOLIDGEN is executed. Two correction sets are needed because SOLIDGEN is contained on two files. One of those files contains that part of SOLIDGEN coded in RATFOR, a programming language which is preprocessed into FORTRAN; the other file contains that part of SOLIDGEN coded in FORTRAN.

The two correction sets may currently be used to change G_{max}, the limit on the number of grid points which can be generated. The current default value of G_{max} is 1,000 and needs to be changed only if more than 1,000 grid points are to be generated.

When the correction sets are used, the card deck for running SOLIDGEN consists of the following four components:

1. Control cards
2. Correction set for file which contains that part of SOLIDGEN coded in RATFOR
3. Correction set for file which contains that part of SOLIDGEN coded in FORTRAN
4. The SOLIDGEN Input Deck

These four components must be separated by "End-of-Record" cards (7, 8, and 9 punches in column 1). The control cards used in the deck are shown in Figure 31. On the card marked "*" the user must enter the identifier for the geometry file (e.g., GEOM, ID=CAXX).

The correction set for the file which contains that part of SOLIDGEN coded in RATFOR (GRPUBLIC, ID=CARK) is shown in Figure 32. On the card marked "*" the user must replace NNNN by G_{max}.

```
C                    JOB CARD
ATTACH,OLDPL,GRPUBLIC,ID=CARK,MR=1.
UPDATE(P,L=0)
ATTACH,RATFOR.
RATFOR,COMPILE,FTO.
REWIND,OUTPUT.
FTN,I=FTO,R=3,OPT=2,EL=A,PL=20000,L=0.
RETURN,OLDPL.
ATTACH,OLDPL,GFPUBLIC,ID=CARK,MR=1.
UPDATE(P,L=0)
FTN,I=COMPILE,R=3,OPT=2,EL=A,PL=20000,L=0.
ATTACH,OLD,BINARYPUBLIC,ID=CARK,MR=1.
COPYL(OLD,LGO,LGONEW,,A)
*ATTACH,UMFX,GEOMETRY FILE,MR=1.
COPYBF,UMFX,UMF.
RETURN,UMFX.
REWIND,UMF.
MSACCES,CARK.
MSFETCH,RIOLIB,UN=GPRM.
ATTACH,SHORTIO.
ATTACH,DATAMAN,CAMVNEWLIB,ID=CARK,MR=1.
MSFETCH,BSPLNLB,UN=GPRM.
ATTACH,GENERLB,ID=GPRM,MR=1.
LIBRARY(FORTRAN,SHORTIO)
LDSET,LIB=GENERLB/BSPLNLB.
LDSET,LIB=RIOLIB/DATAMAN.
LDSET,USE=$PUT.Z$/$PUT.H$.
LDSET,USEP=BRIO/OPENM/CLOSEM.
LGONEW,PL=20000.
EXIT.
DMP,160000.
```

Figure 31 - Control Cards for Running SOLIDGEN with Correction Sets

```
*IDENT RK071179A
*DELETE /TEN/.2
*——►COMMON/TEN/CLASS(32),B(3,32),JX,IN(44),IGL,IG(NNNN),GPC(3,NNNN),
```

Figure 32 - Correction Set for RATFOR Program File

The correction set for the file which contains that part of SOLIDGEN coded in FORTRAN (GFPUBLIC, ID=CARK) is shown in Figure 33. On the card marked "*" the user must replace NNNN by G_{max}.

```
*IDENT RK071179B
*DELETE /TEN/.2
*——►COMMON/TEN/CLASS(32),B(3,32),JX,IN(44),IGL,IG(NNNN),GPC(3,NNNN),
```

Figure 33 - Correction Set for FORTRAN Program File

APPENDIX C

MORE ABOUT DEFINING THE MODEL

Some of the thoughts which appeared in "DEFINING THE MODEL" (in the main body of this report) are developed in additional detail in this appendix. It is hoped that these sections will help the user to better understand the process of defining the model. These sections are also intended to more fully characterize the proper definition of a model.

SOME TERMS WHICH RELATE TO ZONES

A "zone face" is defined as that part of a zone belonging to one of the key reference surfaces which bound the zone. A "zone edge" is defined as that part of a zone belonging to two zone faces and to key reference surfaces in different families. A "corner point" is defined as a point belonging to three of a zone's faces, which belong to key α-, β-, and γ-reference surfaces.

SOME TERMS WHICH RELATE TO ELEMENTS

An "element face" is defined as that part of an element lying in one of the reference surfaces which bound the element. An "element edge" is defined as that part of an element which belongs to two element faces.

THE TOPOLOGICAL MODEL

Suppose that each zone in the model is topologically deformed into a cube while all of the relationships among the zones are preserved. The entity thus created is defined as "the topological model."

Consider a zone whose bounding key reference surfaces are K(1,i), K(1,i+1), K(2,j), K(2,j+1), K(3,k), and K(3,k+1). The α-, β-, and γ-axes may be defined in relation to a cube which is topologically equivalent to that zone. Such a cube, formed by topologically deforming the zone, is shown in Figure 34. The α-axis is defined as follows:

1. It is perpendicular to the zone faces that belong to key α-reference surfaces.

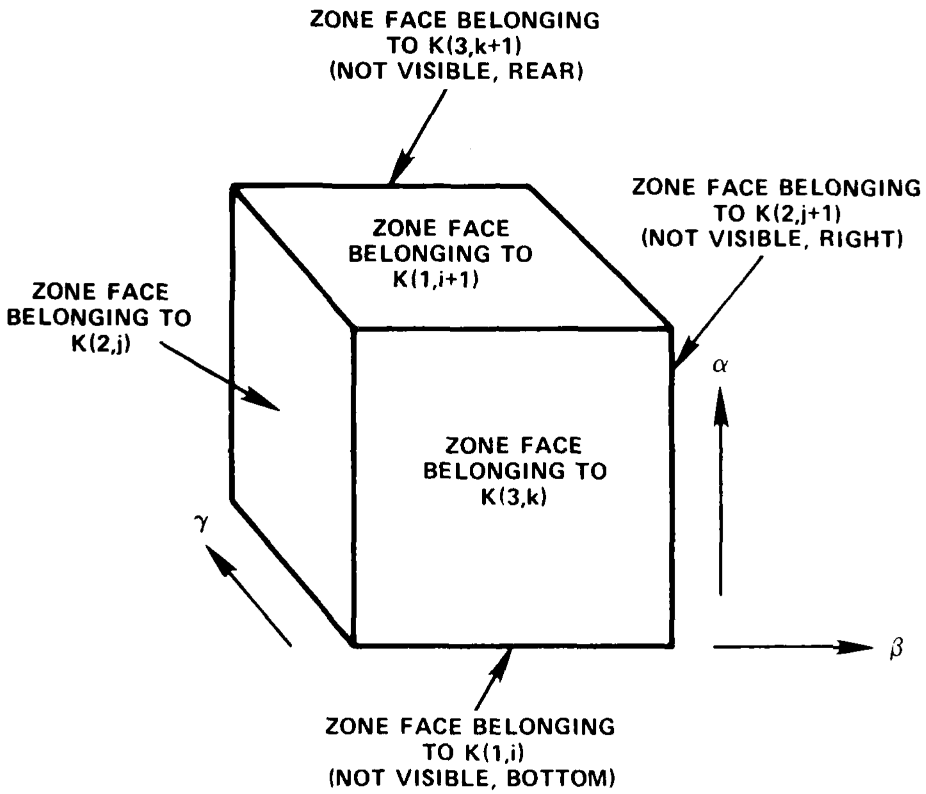


Figure 34 - Cube Topologically Equivalent to Zone with α-, β-, and γ-Axes Shown

2. It is directed from the zone face that belongs to $K(1,i)$ toward the zone face that belongs to $K(1,i+1)$.

The β-axis is defined as follows:

1. It is perpendicular to the zone faces that belong to key β-reference surfaces.
2. It is directed from the zone face that belongs to $K(2,j)$ toward the zone face that belongs to $K(2,j+1)$.

The γ-axis is defined as follows:

1. It is perpendicular to the zone faces that belong to key γ-reference surfaces.
2. It is directed from the zone face that belongs to $K(3,k)$ toward the zone face that belongs to $K(3,k+1)$.

The three axes are also shown for the cube in Figure 34. Because of the numbering system for each key reference surface family (i.e., adjacent key reference surfaces are labeled with consecutive integers) it is clear that the α-, β-, and γ-axes for any zone are identical to these axes for any other zone. Therefore, even though these axes are defined in terms of one zone, their definitions apply to the entire model and may be used in reference to the topological model.

REQUIRED PROPERTIES FOR KEY REFERENCE SURFACES

The following three requirements must be met within the bounds of the desired structural model to ensure that the structural model does not present unresolvable ambiguities to SOLIDGEN:

* If a corner point is needed for the model, the three key reference surfaces on which the corner point lies must intersect at exactly one point.

* If a zone edge is needed for the model, the two key reference surfaces on which the zone edge lies must intersect to form a unique path between the corner points which the zone edge joins.

* The specification of a zone must be unique; i.e., if pairs of adjacent key α-, β-, and γ-reference surfaces are given, they must designate only one zone.

To ensure that an acceptable finite element model will be generated, a fourth requirement is imposed:

* No two key reference surfaces in the same family may intersect within the interior of the structural model.

While this requirement excludes overlapping zones and zones with zero volume, it does not exclude cases in which two key reference surfaces in the same family intersect on the surface of the structural model. Such cases do arise with wedge-shaped zones, i.e., zones for which two edges coincide.

These above four requirements can be referred to as "Requirement 1" (or the "Corner Point Uniqueness Requirement"), "Requirement 2" (or the "Zone Edge Uniqueness Requirement"), "Requirement 3" (or the "Zone Uniqueness Requirement"), and "Requirement 4" (or the "Nonintersecting Key Reference Surface Requirement").

Another requirement can be added: Each zone face needed by the model must be associated with exactly one GPRIME surface. This requirement can be called "Requirement 5" (or the "Unique Zone Face Description Requirement"). (This requirement has already appeared in the main body of this report in "Building Key Reference Surfaces," but was not labeled as a requirement there.)

AN ADDITIONAL NOTE ABOUT THE EXTENT OF GPRIME SURFACES

An earlier section ("Building Key Reference Surfaces") pointed out that a GPRIME surface does not have to coincide with the zone face or zone faces it is being used to describe. Note that, on the other hand, Requirement 1 (Corner

Point Uniqueness Requirement), Requirement 2 (Zone Edge Uniqueness Requirement), and Requirement 3 (Zone Uniqueness Requirement) tend to limit the extent of GPRIME surfaces used for describing zone faces.

APPENDIX D

GENERATING THE MODEL

SOLIDGEN generates the model zone by zone, concentrating on one zone at a time. The method used to generate the finite elements for each zone is briefly described as follows:

* The descriptions of the key reference surfaces are used to compute the coordinates of "zone defining points."
* The "shape functions" are used to subdivide the zone into finite elements.
* "Surface correction" is performed on certain grid points so that they conform to the descriptions of the key reference surfaces.

Generally, this method yields good results, generating desirably shaped finite elements while providing grid points which portray the zone faces accurately.

SUBDIVIDING THE ZONES

The subdivision of each zone into brick elements and the resulting computation of the coordinates of the generated grid points are accomplished by using a method of Zienkiewicz.[7]

Shape Functions

Suppose a zone is bounded by the following key reference surfaces:

K(1,i)

K(1,i+1)

K(2,j)

K(2,j+1)

K(3,k)

K(3,k+1).

Let that zone be called "Zone N." The following explanation refers to Zone N, which, except for being bounded by the key reference surfaces just mentioned, is completely general. Let the spatial (physical) description of the object being modeled be expressed in terms of the Cartesian coordinates x, y, z. Zone N is mapped into the parametric coordinates ξ, η, ζ according to the following rules:

1. ξ is constant on each α-reference surface
2. η is constant on each β-reference surface
3. ζ is constant on each γ-reference surface
4. $\xi = -1$ on K(1,i)
5. $\xi = 1$ on K(1,i+1)
6. $\eta = -1$ on K(2,j)
7. $\eta = 1$ on K(2,j+1)
8. $\zeta = -1$ on K(3,k)
9. $\zeta = 1$ on K(3,k+1)
10. The constant values of ξ on the interior α-reference surfaces are uniformly spaced between -1 and 1
11. The constant values of η on the interior β-reference surfaces are uniformly spaced between -1 and 1
12. The constant values of ζ on the interior γ-reference surfaces are uniformly spaced between -1 and 1

"Zone defining points" are those points that exist for the object being modeled and for which the spatial location (i.e., x, y, z) is known. There are two kinds of zone defining points:

1. corner points
2. midside points

The term "corner points" has already been defined. The midside points describe the zone edges except at corner points. Figure 35 shows an example of zone defining points for a zone, each of whose zone edges is defined by two midside points. The mapping of the corner points for Zone N into the coordinates ξ, η, ζ should already be clear, since each corner point is located on three key reference surfaces.

Three classes of midside points are defined as follows: Class 1, Class 2, and Class 3 midside points are those located, respectively, on Type 1, Type 2, and Type 3 zone edges. Since each midside point is located on two key reference surfaces, the mapping of any given midside point into the coordinates ξ, η, ζ should already be clear for two of the three coordinates. Class 1 midside points can be mapped into ξ, Class 2 midside points into η, and Class 3 midside points into ζ according to the following rules:

1. On each Type 1 zone edge the values of ξ at the midside points are uniformly spaced between -1 and 1. (Similar statements apply to η and ζ on Type 2 and Type 3 zone edges, respectively.)

2. It is not necessary that a Class 1 midside point be located on any of the interior α- reference surfaces of Zone N. (Similar statements apply to Class 2 and Class 3 midside points .)

The spatial coordinates for any grid point that is needed for Zone N can then be computed as follows:

$$x = \sum_{i=1}^{M} N_i (\xi, \eta, \zeta) x_i$$

$$y = \sum_{i=1}^{M} N_i (\xi, \eta, \zeta) y_i$$

$$z = \sum_{i=1}^{M} N_i (\xi, \eta, \zeta) z_i$$

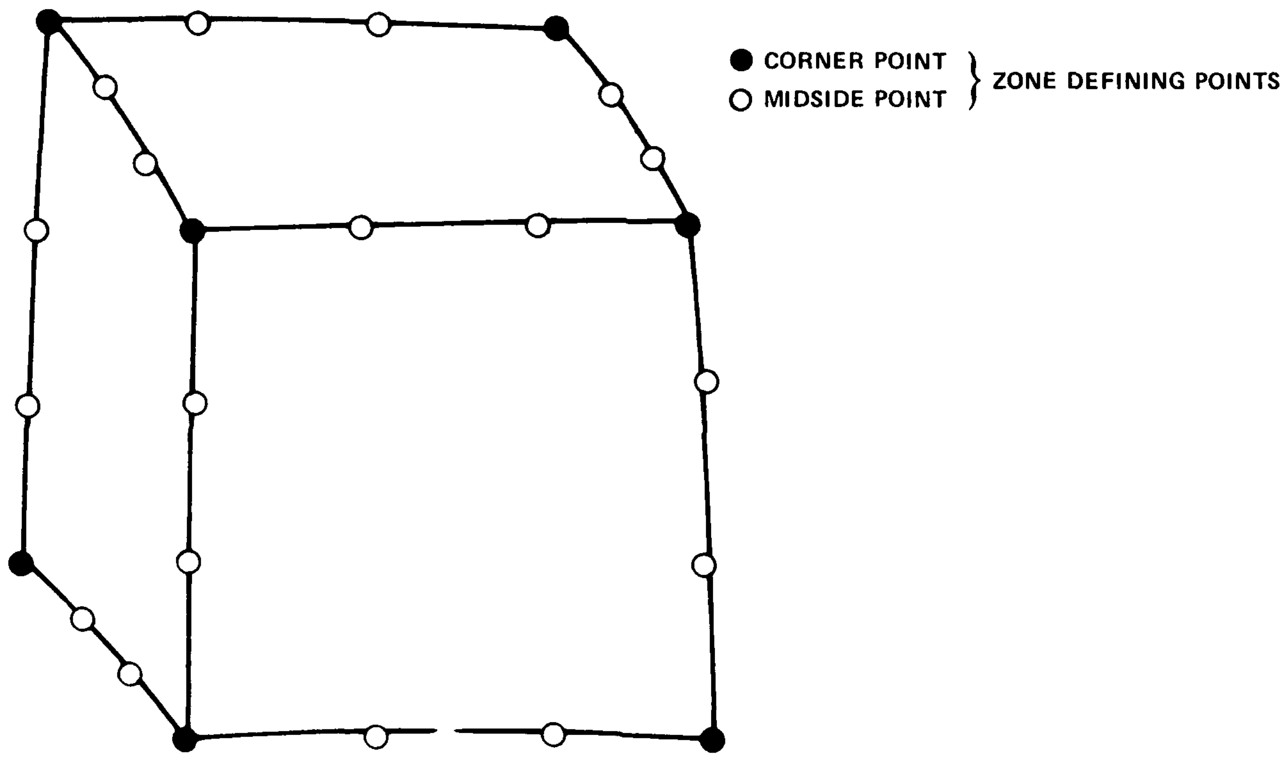


Figure 35 - Example of Zone as Defined by Shape Functions

where

$$M = \text{Number of zone defining points for Zone N},$$

$$x_i,\ y_i,\ z_i = \text{the spatial location of the } i^{th} \text{ zone defining point},$$

and

$N_i(\xi, \eta, \zeta)$ = "shape function" for the i^{th} zone defining point.

The shape functions are given by Table 8, where

$$\xi_0 \equiv \xi\xi_i,$$

$$\eta_0 \equiv \eta\eta_i,$$

$$\zeta_0 \equiv \zeta\zeta_i,$$

ξ_i, η_i, ζ_i is the parametric location of the i^{th} zone defining point, and

ξ, η, ζ is the parametric location of the grid point.

Finding Zone Defining Points

SOLIDGEN uses the key reference surface descriptions furnished by the user to compute the coordinates of the zone defining points. Although the user need not be directly concerned with obtaining the zone defining points, the process is described here for those interested.

When a certain corner point is needed, the program looks for an occupied zone (Zone N) which uses that corner point. If the corner point belongs to K(1,i), K(2,j), and K(3,k), the corresponding three GPRIME surfaces for Zone N are then found. The names of the three surfaces are checked for validity and distinctness, and the point of intersection of the three surfaces is found. That point is then used as the corner point. If this procedure does not yield the desired corner

TABLE 8 - SHAPE FUNCTIONS

Number of Midside Points on Each Zone Edge	$N_i(\xi,\eta,\zeta)$	Zone Defining Point
0	$\frac{1}{8}(1+\xi_o)(1+\eta_o)(1+\zeta_o)$	Corner Point
1	$\frac{1}{8}(1+\xi_o)(1+\eta_o)(1+\zeta_o)(\xi_o+\eta_o+\zeta_o-2)$	Corner Point
	$\frac{1}{4}(1-\xi^2)(1+\eta_o)(1+\zeta_o)$	Midside Point, Class 1
	$\frac{1}{4}(1+\xi_o)(1-\eta^2)(1+\zeta_o)$	Midside Point, Class 2
	$\frac{1}{4}(1+\xi_o)(1+\eta_o)(1-\zeta^2)$	Midside Point, Class 3
2	$\frac{1}{64}(1+\xi_o)(1+\eta_o)(1+\zeta_o)[9(\xi^2+\eta^2+\zeta^2)-19]$	Corner Point
	$\frac{9}{64}(1-\xi^2)(1+9\xi_o)(1+\eta_o)(1+\zeta_o)$	Midside Point, Class 1
	$\frac{9}{64}(1+\xi_o)(1-\eta^2)(1+9\eta_o)(1+\zeta_o)$	Midside Point, Class 2
	$\frac{9}{64}(1+\xi_o)(1+\eta_o)(1-\zeta^2)(1+9\zeta_o)$	Midside Point, Class 3

point, the program looks for another occupied zone which uses the corner point and follows a similar procedure. Once the corner point has been successfully obtained by using the zone faces of one zone, no attempt is made to obtain the corner point by using the zone faces of any other zone. That is, the program does not attempt to verify that Requirement 6 (Corner Point Compatibility Requirement; see Appendix E) has been satisfied, because of the excessive computing time that would be involved.

In the procedure for obtaining the midside points on a given zone edge, the program assumes that the corner points which lie at the ends of the zone edge (points "A" and "B") have already been obtained. Let M be the number of midside points required on the zone edge. The program looks for an occupied zone (Zone N) which uses that zone edge. If the zone edge belongs to two key reference surfaces (S and T) from different families, the two GPRIME surfaces associated with the zone faces of Zone N which belong to S and T are found. A set of surfaces is formed from M planes which are perpendicular to AB (line segment) and which pass through M uniformly spaced intermediate points on AB. The names of the two GPRIME surfaces are checked for validity and distinctness, and the point of intersection of the two GPRIME surfaces and each of the M planes is found. The M points thus formed are then used as the midside points. If this procedure does not yield the desired midside points, the program looks for another occupied zone which uses the zone edge and then follows a similar procedure. Once the midside points have been successfully obtained by using the zone faces of one zone, no attempt is made to obtain the midside points by using the zone faces of any other zone. That is, the program does not attempt to verify that Requirement 7 (Zone Edge Compatibility Requirement; see Appendix E) has been satisfied, because of the excessive computing time that would be involved.

Choosing Number of Midside Points

Because the program uses the method just described, the user must decide how many midside points to use on each zone edge in accordance with the following requirements:

1. All zone edges must use the same number ("N") of midside points.
2. N must be 0, 1, or 2.

Generally, N should be 2. However, if all zone edges are known to be straight line segments, N may be 0 or 1. If the user does not assign a value to N, it will automatically be set to 2 by the program.

USE OF SHAPE FUNCTIONS AND SURFACE CORRECTION

Using the shape functions to subdivide the zones creates a need for the procedure called "surface correction."

Why Surface Correction Is Necessary

While a given zone is defined by shape functions in terms of its zone defining points, the user describes that same zone by specifying that each zone face is associated with a certain GPRIME surface. Thus, the exterior of the zone as portrayed by the shape functions generally coincides with the exterior of the zone as defined by the user only at the zone defining points. (The word "portrayed" is used here to reflect the fact that the shape functions generate only a finite number of grid points for a given zone but "visualize" that same zone in a continuous manner, i.e., in its entirety.) Therefore, each grid point which lies on the interior of a given zone face (i.e., on the zone face but not on any zone edge) as portrayed by the shape functions must be modified so that it actually lies on the zone face as defined by the user, i.e., on the GPRIME surface associated with the zone face. Similarly, each grid point which lies on a given zone edge as portrayed by the shape functions must be modified so that it actually lies on the zone edge as defined by the user, i.e., on the GPRIME surfaces associated with the two zone faces to which the zone edge belongs. This process of modifying grid points is called "surface correction." The first kind of surface correction (correction to interior of zone face) is called "Type 1 surface correction" and the second kind (correction to zone edge) "Type 2 surface correction."

Figure 36 illustrates the need of a typical zone for surface correction. The zone in Figure 36 is subdivided into two elements. The grid points labeled "A" require Type 1 surface correction; the grid points labeled "B" require Type 2 surface correction.

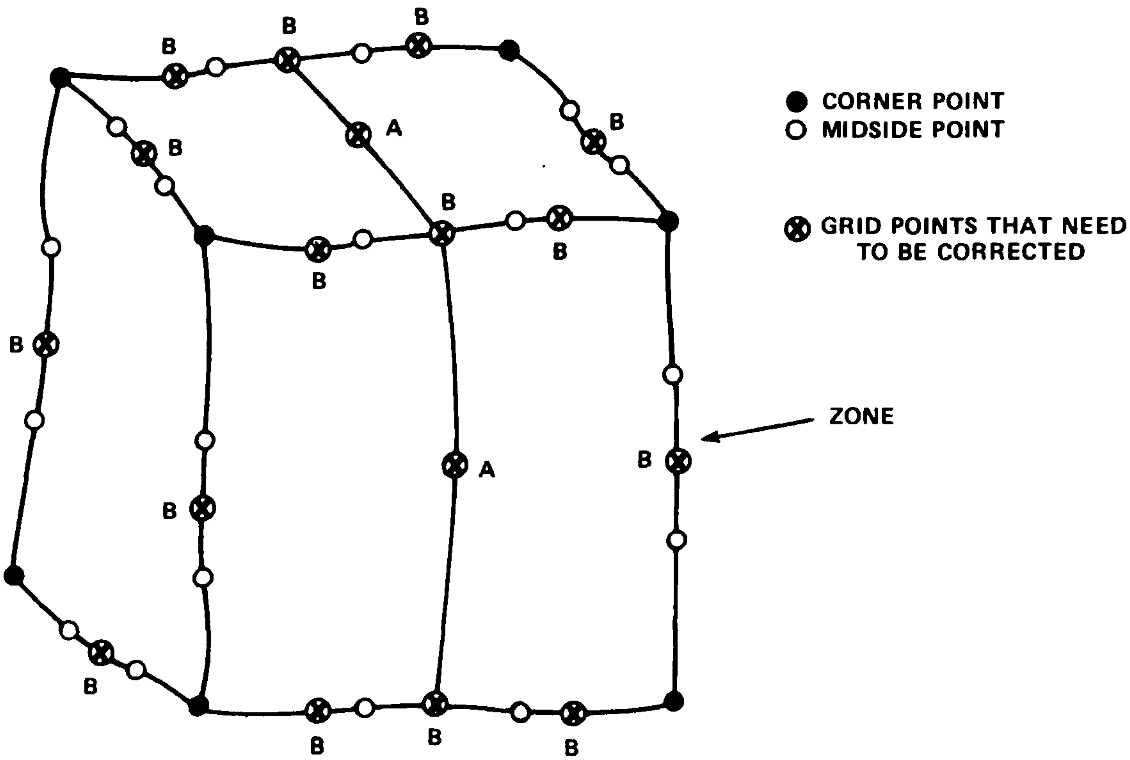


Figure 36 - The Need for Surface Correction

Method

Since SOLIDGEN performs the procedures described below, the user need not be directly concerned with them; they are described here for those interested.

For Type 1 surface correction, SOLIDGEN finds the straight line which (1) is normal to the zone face as portrayed by the shape functions at the grid point generated by the shape functions and (2) passes through that grid point. The point of intersection of that straight line with the GPRIME surface associated with the zone face is the corrected grid point.

For Type 2 surface correction, SOLIDGEN finds the plane which (1) is normal to the zone edge as portrayed by the shape functions at the grid point generated by the shape functions and (2) passes through that grid point. The point of intersection of that plane with the (two) GPRIME surfaces associated with two zone faces to which the zone edge belongs is the corrected grid point. Although both zone faces will usually belong to the zone used by the shape functions to generate the grid point, certain conditions encountered during the computation of the corrected grid point can cause another pair of zone faces to be used.

Although the obvious approach to performing bot types of surface correction would seem to be to find the closest point on the appropriate GPRIME surface or surfaces, the methods just described are much more economical in terms of computer time.

Avoiding Undesired Effects

If a zone, as portrayed by the shape functions, differs greatly from the same zone as defined by the user, surface correction for one or more grid points may be so severe that one or more undesirably shaped or, in the worst case, distorted elements will be generated. For a grid point on which Type 1 surface correction has been performed, the process of moving the grid point to the GPRIME surface associated with the zone face may push the grid point too far into the interior o the zone as portrayed by the shape functions. (Remember that nothing is done to grid points in the interior of the zone after those grid points have been generated by the shape functions.) For a grid point on which Type 2 surface correction has been performed, the effect can occur in two ways: (1) If the grid

point as generated by the shape functions lies on neither of the two GPRIME surfaces associated with the zone faces to which the zone edge belongs, the process of moving the grid point to both of those GPRIME surfaces may push the grid point too far into the interior of the zone as portrayed by the shape functions; (2) if the grid point as generated by the shape functions already lies on one of the two GPRIME surfaces associated with the zone faces to which the zone edge belongs, the process of moving the grid point to the other GPRIME surface pushes the grid point too far into the interior of the zone face. This occurs because, although the grid points on the interior of the zone face (grid points on which Type 1 surface correction has been performed) lie on the exterior of the zone as defined by the user, i.e., on the GPRIME surface associated with the zone face, their generation involves no information about the zone edges which border the zone face.

Generally, such undesirable effects can be avoided by

1. Using shape functions of higher order, i.e., more midside points on each zone edge, or

2. Adding one or more key reference surfaces to the existing model in appropriate places, thereby replacing zones which are unsatisfactory in the manner described above by more acceptable zones.

Some Useful Properties Of The Generated Model

The use of the shape functions for obtaining the coordinates of the grid points and the subsequent application of surface correction to some of those grid points result in some useful properties of the generated model.

Zone Edges. An inspection of the shape functions of a certain zone (Zone M) will show that a given zone edge of Zone M, as portrayed by the shape functions, depends only on the zone defining points which lie along the zone edge, i.e., the corner points at the ends of the zone edge and the midside points which lie on the zone edge. For another zone (Zone N), the zone edge as portrayed by the shape functions during the generation of Zone M is identical to the zone edge as portrayed by the shape functions during the generation of Zone N. Compare the results of obtaining the grid points on the zone edge by the following two methods:

1. The grid points on the zone edge are obtained during the generation of Zone M
2. The grid points on the zone edge are obtained during the generation of Zone N.

In the actual model generation, of course, each grid point is generated only once. Each grid point on the zone edge which does not coincide with a corner point or midside point is obtained by performing Type 2 surface correction on the grid point which lies on the zone edge as portrayed by the shape functions. We can see that the grid points on the zone edge obtained during the generation of Zone M are identical to the grid points on the zone edge obtained during the generation of Zone N. This has the following useful implication: If there are two models whose key reference surfaces (i.e., zone faces) as defined by the user are identical but whose occupied zones are different, each grid point on a zone edge in one model will be identical to the corresponding grid point in the other model. This is a useful property because it means that the grid points on the zone edges are generated independently of the way in which the zones are occupied.

Suppose that two zones in the model have no common zone edges, i.e., the two zones are completely separate topologically. Consider two zone edges, each of which belongs to one of the zones. If the user defines the zone edges so that they coincide (which will cause the zone defining points for one zone edge to coincide with the zone defining points for the other zone edge) and the zone edges have the same number of interior reference surfaces between their bounding corner points, the grid points generated on the zone edges will be identical. This property is useful in two ways: (1) When a zone edge of one of those zones needs to be glued to a zone edge of the other zone, and (2) when two independently generated sections of the model need to be glued together, as when a large or complex model is to be assembled from independently generated parts.

Zone Faces. An inspection of the shape functions of a certain zone (Zone M) will show that a given zone face of Zone M as portrayed by the shape functions depends only on the zone defining points which border the zone face. This zone face is identical to the zone face as portrayed by the shape functions during the generation of an adjoining zone, Zone N. Now compare the results of obtaining the grid

points on the interior of the zone face (i.e., those grid points on the zone face which do not lie on any of its bordering zone edges) by the following two methods:

1. The grid points on the interior of the zone face are obtained during the generation of Zone M

2. The grid points on the interior of the zone face are obtained during the generation of Zone N.

In the actual model generation, of course, each grid point is generated only once. Each grid point on the interior of the zone face is obtained by performing Type 1 surface correction on the grid point which lies on the interior of the zone face as portrayed by the shape functions. The grid points on the interior of the zone face obtained during the generation of Zone M are identical to the grid points on the interior of the zone face obtained during the generation of Zone N. This, along with the conclusion reached about grid points on zone edges in the preceding section, has the following useful implication: If there are two models whose key reference surfaces (i.e., zone faces) as defined by the user are identical but whose occupied zones are different, each grid point on a zone face in one model will be identical to the corresponding grid point in the other model. This property is useful because it means that the grid points on the zone faces are generated independently of the way in which the zones are occupied.

Suppose that two zones in the model have no common zone edges, i.e., the two zones are completely separate topologically. Consider two zone faces, each of which belongs to one of the zones. If the zone faces are defined so that they coincide (which will cause the zone defining points which border one zone face to coincide with the zone defining points which border the other zone face) and the zone faces have the same number of interior reference surfaces between corresponding pairs of their bounding zone edges, the grid points generated on the zone faces will be identical. If a zone face of one of those zones needs to be glued to a zone face of the other zone, the model can be defined so that the two zone faces coincide. Two zone faces can also be matched in this way when two independently generated sections of the model need to be glued together, as when a large or complex model is to be assembled from independently generated parts.

APPENDIX E

FURTHER DEVELOPMENT OF DEFINITIONS AND REQUIREMENTS

SOME USEFUL NOTATION FOR CORNER POINTS AND ZONE EDGES

Since the zones are an integral part of the network of key reference surfaces, certain parts of a given zone can belong to more than one zone. That is:

* A corner point can belong to as many as eight zones.
* A zone edge can belong to as many as four zones.
* A zone face can belong to one zone or two zones.

Some of the parts previously defined in terms of individual zones can thus also be defined in terms of the network of key reference surfaces.

C(i,j,k), a corner point, is defined as follows: C(i,j,k) is the corner point which belongs to K(1,i), K(2,j), and K(3,k).

E(i,j,k,m), a zone edge, can also be defined (where m is 1, 2, or 3). E(i,j,k,1) is the zone edge formed by that part of the intersection of K(2,j) and K(3,k) which lies between K(1,i) and K(1,i+1). E(i,j,k,2) is the zone edge formed by that part of the intersection of K(1,i) and K(3,k) which lies between K(2,j) and K(2,j+1). E(i,j,k,3) is the zone edge formed by that part of the intersection of K(1,i) and K(2,j) which lies between K(3,k) and K(3,k+1). Note, also, that "m" indicates the zone edge type for E(i,j,k,m); that is, E(i,j,k,m) is a Type m zone edge.

E(i,j,k,m) can be described in another way which, although not equivalent to the formal definition, might be helpful:

* E(i,j,k,1) is the zone edge which joins C(i,j,k) and C(i+1,j,k)
* E(i,j,k,2) is the zone edge which joins C(i,j,k) and C(i,j+1,k)
* E(i,j,k,3) is the zone edge which joins C(i,j,k) and C(i,j,k+1).

RESTATEMENT OF REQUIREMENT 1 AND REQUIREMENT 2

With the help of this notation, Requirement 1 (Corner Point Uniqueness Requirement) can be restated as follows:

* If a corner point, C(i,j,k), is needed for the model, K(1,i), K(2,j), and K(3,k) must intersect at exactly one point.

Similarly, Requirement 2 (Zone Edge Uniqueness Requirement) can be restated and expanded:

* If a zone edge, E(i,j,k,m), is needed for the model, the key reference surfaces must form a unique path between the corner points which that zone edge joins.

This requirement can also be described for each of the three types of zone edges. If E(i,j,k,1) is needed for the model, K(2,j) and K(3,k) must intersect to form a unique path between C(i,j,k) and C(i+1,j,k). If E(i,j,k,2) is needed for the model, K(1,i) and K(3,k) must intersect to form a unique path between C(i,j,k) and C(i,j+1,k). If E(i,j,k,3) is needed for the model, K(1,i) and K(2,j) must intersect to form a unique path between C(i,j,k) and C(i,j,k+1).

COMPATIBILITY REQUIREMENTS FOR ZONE FACES

Because the zone faces which make up a given key reference surface are, in general, not all associated with the same GPRIME surface, and because all the zone faces which make up the model must fit together so that the key reference surfaces are properly defined, the zone faces must be associated with GPRIME surfaces so that certain requirements are satisfied.

If C(i,j,k) belongs to Zone m, "C(i,j,k) as seen by Zone m" is defined as the point of intersection of the following three surfaces:

* The GPRIME surface associated with the zone face of Zone m which belongs to K(1,i)

* The GPRIME surface associated with the zone face of Zone m which belongs to K(2,j)

* The GPRIME surface associated with the zone face of Zone m which belongs to K(3,k).

We then have the following requirement: C(i,j,k) as seen by Zone m must be identical to C(i,j,k) as seen by Zone n, where Zone m and Zone n are any two zones to which C(i,j,k) belongs. That is, the zone faces at a corner point must be compatible. This requirement is referred to as "Requirement 6" (or the "Corner Point Compatibility Requirement"). Note that Requirement 6 actually stems from Requirement 1 (Corner Point Uniqueness Requirement) plus the fact that the zone faces of a given key reference surface need not all be associated with the same GPRIME surface.

Before a compatibility requirement for zone edges can be stated, "E(i,j,k,m) as seen by Zone n" needs to be defined for m = 1, 2, and 3.

If E(i,j,k,1) belongs to Zone n, "E(i,j,k,1) as seen by Zone n" is defined as the curve of intersection (between C(i,j,k) and C(i+1,j,k)) formed by the following two surfaces:

* The GPRIME surface associated with the zone face of Zone n which belongs to K(2,j)

* The GPRIME surface associated with the zone face of Zone n which belongs to K(3,k).

If E(i,j,k,2) belongs to Zone n, "E(i,j,k,2) as seen by Zone n" is defined as the curve of intersection (between C(i,j,k) and C(i,j+1,k)) formed by the following two surfaces:

* The GPRIME surface associated with the zone face of Zone n which belongs to K(1,i)

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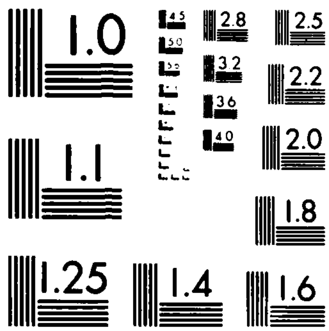

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* The GPRIME surface associated with the zone face of Zone n which belongs to K(3,k).

If E(i,j,k,3) belongs to Zone n, "E(i,j,k,3) as seen by Zone n" is defined as the curve of intersection (between C(i,j,k) and C(i,j,k+1)) formed by the following two surfaces:

* The GPRIME surface associated with the zone face of Zone n which belongs to K(1,i)

* The GPRIME surface associated with the zone face of Zone n which belongs to K(2,j).

We then have the following requirement: E(i,j,k,m) as seen by Zone n must be identical to E(i,j,k,m) as seen by Zone p, where Zone n and Zone p are any two zones to which E(i,j,k,m) belongs. That is, the zone faces at a zone edge must be compatible. This requirement is referred to as "Requirement 7" (or the "Zone Edge Compatibility Requirement"). Note that Requirement 7 actually stems from Requirement 2 (Zone Edge Uniqueness Requirement) plus the fact that the zone faces of a given key reference surface need not all be associated with the same GPRIME surface.

Even though Requirement 6 is really a special case of Requirement 1 and Requirement 7 is a special case of Requirement 2, it is felt that their explicit statement provides additional insight into the process of describing key reference surfaces.

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